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THESIS

A Transduction Path Method of Solid State Sensor Analysis and Investigation

by

Curtis L. Dubay

September 1984

Thesis Advisor: Rudolph Panholzer

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This paper proposes a "transduction path" method of analysis for solid state sensors. It is based upon the idea that a sensor represents a transduction path from some input measurand to an electrical output. The transduction path may consist of one or more transduction or modification principles drawn from all fields of science. Also proposed is a "transduction path diagram" which provides a graphical representation of a transduction path.

Background material concerning the development and description of solid state sensors is presented. Sensor measurands are identified and categorized by energy form. The known transduction and modification principles are presented as fundamental building blocks of the transduction path and cross-indexed by measurand. The transduction path diagram is introduced and examples of existing single and multistep transducers are presented. Finally, the transduction path method is shown to be valuable as a systematic method of investigating sensor configurations.

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A Transduction Path Method of Solid State Sensor Analysis and Investigation

by

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requirements for the degree of

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ABSTRACT

This paper proposes a "transduction path" method of analysis for solid state sensors. It is based upon the idea that a sensor represents a transduction path from some input measurand to an electrical output. The transduction path may consist of one or more transduction or modification principles drawn from all fields of science. Also proposed is a "transduction path diagram" which provides a graphical representation of a transduction path. Background material concerning the development and description of solid state sensors is presented. Sensor measurands are identified and categorized by energy form. The known transduction and modification principles are presented as fundamental building blocks of the transduction path and cross-indexed by measurand. The transduction path diagram is introduced and examples of existing single and multistep transducers are presented. Finally, the transduction path method is shown to be valuable as a systematic method of investigating sensor configurations.

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I. INTRODUCTION

A. DEFINITIONS

In order to gain an understanding of solid state sensor operation and their capabilities, it is necessary to present a few definitions. For the purpose of this paper, a solid state sensor may be regarded as a device that converts a physical quantity, or measurand, into an electrical signal of significant fidelity that is compatible with integrated circuit technology and relies upon the principles of solid state physics for its operation. The measurand represents information about an aspect of the physical world which, for one reason or another, is the object of measurement. This information is carried by a signal which is characterized as belonging to one of seven different forms of energy. These forms include mechanical, thermal, electrical, magnetic, optical, chemical, and nuclear energy.

The process by which one form of energy is converted into another form of energy is known as transduction. For instance, a light emitting diode is a transducer which converts electrical energy to optical energy. Likewise, a photocell performs the inverse operation, and transduces optical energy to electrical energy. The process by which one form of energy is changed to a like form of energy is known as modification or signal processing. An example of a mechanical to mechanical modifier would be the gear system in the transmission of an automobile. The energy form is not changed, but the mechanical angular velocity of the output is different from that of the input. Another example of a modifier is the operational amplifier, which may be regarded as an electrical to electrical modifier, or signal processor. An electrical signal is applied to the input and a processed electrical signal is extracted at the output.

In a solid state sensor, the conversion of a measurand into an electrical signal takes place along a transduction path, which consists of one or more discrete transduction or modification steps. This transduction path approach is central to the subject of this paper and will be addressed in detail in later chapters. The basic concepts of sensors are closely related to the topic of instrumentation which is discussed fully in [Ref. 1].

B. TRADITIONAL SENSORS

The development of science throughout history has been closely tied to man's ability to sense, or measure, the world around him. Man possesses five natural senses which enable him to detect physical phenomena, but only within set limits of perception and only in his presence. In time, a need developed for devices that would sense physical phenomena outside of man's natural limits or not in his presence. These devices are referred to as sensors or transducers, and represent a means by which man can expand his natural senses to perceive more of the physical world than would otherwise be possible.

The generation of sensors and transducers that precedes solid state sensors may be referred to as the traditional generation of sensors. This generation is characterized by a physical scale that is compatible with design and fabrication by the human hand and eye. While some automation is typically used in the fabrication of such devices, the physical scale is usually compatible with some degree of hand assembly. Illustrative examples of the traditional generation of sensors include the mercury thermometer, aneroid barometer and pendulum clock. These devices convert, or transduce, temperature, pressure, or time into a mechanical signal that man is capable of sensing and interpreting. This mechanical signal contains the information about the aspect of the physical world under measurement.

The traditional sensors possess several disadvantages that make the next generation of sensors, solid state, very attractive. Chief among these disadvantages are size and cost. The part count of a traditional sensor tends to be comparatively high. This, coupled with a feature size compatible with the human hand and eye, results in a sensor of considerable bulk and weight. This is particularly true when a comparison is made with integrated circuit devices fabricated by photolithography with a feature size on the order of a few microns. The high part count and considerable reliance on hand assembly combine to make the traditional generation of sensors expensive. In the next section, we shall see how solid state sensors became necessary to alleviate some of these problems and make inexpensive sensing possible.

C. SOLID STATE SENSORS

Recent advances in the fabrication of integrated circuits have brought about a revolution in the field of information processing. Single chip microcomputers of considerable capability have appeared that are making the concept of component computers a reality. With the increased flexibility that this provides in the development of new and complex systems, electronics is infiltrating into more fields than ever before. But the increased capacity for information processing in turn gives rise to a need for increased input of data or information pertaining to the physical world. In the past, much of this information from the physical world has been detected by humans or machines and subsequently encoded into the processor as data. To make efficient use of the speed with which modern microcomputers operate, the data collection process likewise has to be fast and efficient.

Solid state sensors represent a means by which data on physical phenomena may be rapidly collected and assimilated. They convert a measurand into an electrical signal that can be subsequently changed into digital data through the process of analog to digital conversion. This data collection process can fall into two main categories. The first is that of the real time transducer which continuously monitors the measurand and provides continuous data for processing. The second is that of the non-real time transducer which is used primarily to determine the status of a particular measurand and may be activated only when a preset threshold is exceeded [Ref. 2].

In the past, the cost of computing power was so prohibitive that it precluded the use of microcomputers in many applications. However, batch fabrication techniques and advances in integrated circuit design have brought the cost of microprocessors and microcomputers down to a level where they have become economical as component computers. In many applications of microcomputers, it is found that much of the cost resides in the peripheral devices rather than the processor itself. In the particular case of sensor input to a microcomputer, a need arose for inexpensive devices that would carry out the functions of data collection and dissemination. The problem reduced to one of efficiently merging the fields of sensors and microprocessors. As it turned out, the silicon integrated circuit industry provided many of the techniques necessary to fabricate such devices.

The most common materials for the fabrication of solid state sensors are silicon, doped silicon, quartz, and optical fibers. Solid state sensors constructed of silicon enjoy many of the advantages of batch fabrication techniques developed by the silicon integrated circuit industry. Much of the wealth of experience gained in processing silicon for integrated circuits has been useful in developing solid state sensors. In this respect, it can be said that silicon solid state sensor technology has developed on the coattails of integrated circuit technology.

Like integrated circuits, the physical scale of solid state sensors is limited only by the resolution of the photolithography techniques employed. This represents a major improvement over the previous generation of sensors which is characterized by a physical scale compatible with hand assembly on a per-unit basis.

The silicon used in the fabrication of sensors is a single crystal which makes the sensor a monolithic device with practically no measurable hysteresis. Using silicon as a substrate material also opens the possibility of a sensor with onboard signal processing using integrated circuit technology. Carried to the extreme, this could mean the development of a smart sensor with its own dedicated microcomputer on board. One advantage of such an arrangement would be that inherently nonlinear transduction principles could be utilized without substantial penalty [Ref. 3]. Such an arrangement could also take advantage of the fact that silicon integrated circuits have a mean time to failure of 10^{11} hours per gate which is 10^{3} times better than that of discrete transistor circuits and 10^{5} times better than that of vacuum tube circuits [Ref. 4]. This, coupled with the exceptional physical properties of single crystal silicon, makes possible a generation of sensors with onboard signal processing of much greater reliability than ever before.

Other performance characteristics of sensors that should be considered include accuracy, linearity of response, size, weight and dynamic range. Accuracy of solid state sensors is often superior to the traditional sensors owing to the lack of hysteresis in monolithic silicon. As noted before, a nonlinear characteristic can be negated as a drawback when proper signal processing is applied. Often, this also gives rise to an increased dynamic range when the sensor is no longer restricted to the linear portion of the characteristic curve. Solid state sensors enjoy a firm advantage over traditional sensors in the areas of size and weight since solid state sensors benefit from many of the advantages of modern photolithography techniques.

The other mediums commonly used for solid state sensors share many of the same advantages as silicon solid state sensors. However, the use of optical fiber as a sensing medium offers the option of a distributed sensing element of tremendous sensitivity. As the wavelength of light is so very short in comparison to many of the phenomena being measured, very high resolution is possible.

D. APPLICATIONS

As sensors truly represent a link between the worlds of applied physics and electronics, it is likely that the future will see the role of solid state sensors continuing to expand. One area in which solid state sensors have become very important is the field of automotive electronics. Nearly all domestic cars being produced now contain at least one sensor under microprocessor control [Ref. 3]. One of the reasons the field of automotive electronics has grown so rapidly is that current technology has made such techniques economically feasible. The automotive engineer now has a whole new set of tools with which he can work to improve engine efficiency and ensure compliance with emission standards. By monitoring such critical engine parameters as crankshaft angle position, manifold absolute pressure, manifold vacuum, ambient absolute pressure, air flow, oxygen partial pressure, fuel flow, coolant temperature, air temperature, and throttle position, the automotive engineer can control engine performance as never before possible [Ref. 5]. Excellent summaries of automotive engine control sensor technology are available in References 5-8. Also, it is interesting to note that Detroit uses more absolute pressure sensors in one year than had been produced everywhere for all purposes up to the year 1980 [Ref. 3].

Another area seeing important progress in implementation of solid state sensors is that of robotics. Many of the robotic arms that have been developed rely upon mechanical rigidity for repeatability of movement. Construction techniques allowing precision movements within strict tolerances have been heavily relied upon. By employing sensor feedback with real-time microprocessor control systems, it should be possible to utilize a comparatively sloppy and loose manipulator for exacting applications. Additionally, robotic navigation and collision avoidance become possible when sensor feedback is introduced into the system. Much work is currently being carried out in this area. Useful background information on sensor based robotics is contained in [Ref. 9].

Other applications for solid state sensors include cameras, appliances, biomedical instruments, spacecrafts, weapons, antipollution devices, weather monitoring equipment, and microprocessor-based control systems in industry.

II. OBJECTIVES

A. PROBLEM STATEMENT

The field of solid state sensors encompasses a tremendously diverse body of knowledge. Principles from all of the known fields of science are employed in solid state sensor design. On one side of a solid state state sensor is the physical world. This physical world is the province of many specialists, including chemists, physicists, and mechanical engineers, to name only a few. On the other side of a solid state sensor is the world of electronics. This is the express province of the electrical engineer. Serving as a bridge between the world of pure physical science and the world of electronics is a hybrid field, that of the sensor and transducer engineer.

Due to the extremely diverse nature of the field, a problem exists for the electrical engineer interested in solid state sensors. A method has been lacking by which the entire range of sensors, both actual and theoretical, may be systematically described. Such a method would make it possible to examine the entire field in such a manner that it would be possible to determine where implementation has fallen short of theoretical possibility. The method needs to be able to describe existing sensors as well as aid in the investigation of sensor configurations.

B. CURRENT METHODS

The first step towards such a work is an evaluation of the current state of the technology. In order to perform such an evaluation, it is necessary to review the manner in which a transducer is currently described.

During the 1960's, a great variety of traditional sensors and transducers became available in support of the space program. A need developed for a standardized method of specifying sensors and transducers. Such a standard was developed under the auspices of the Instrument Society of America in 1969 and accepted as American National Standard, ANSI MC6.1-1975 in 1975 [Ref. 10]. The practices set forth by this standard specify that a sufficient description is given when the measurand, the transduction principle, the sensing element, the range, and any special features are specified.

The measurand represents that quantity which is intended to be measured. The transduction principle is the operating principle of the electrical portion of the transducer from which the output originates. The sensing element is that physical part of the transducer which directly responds to the input measurand. Examples of special features may include digital output and temperature compensation. The range is described by the upper and lower limits of the measurand between which the transducer is intended to operate. As an illustrative example, a Hall effect current sensor could be described as "Transducer, current, Hall effect, non-contact, 0-1 Amp". [Ref. 10]

C. PROPOSED SOLUTION

As seen above, the standard only specifies the last step of the transduction process, which converts the measurand to an electrical signal. However, many transducers are multistep devices which utilize more than a single transduction or modification process. To account for this, and allow greater flexibility in describing sensors, a "transduction path" method of analysis is hypothesized. It is based on the idea that a sensor represents a transduction path from a measurand to an electrical quantity. The transduction path consists of one or more discrete transduction or modification steps. The transduction path may be illustrated in graphical form through a "transduction path diagram". This diagram is capable of not only describing the operation of existing sensors, but also may aid in the systematic investigation of sensor configurations.

D. PROCEDURE

This paper proposes a "transduction path" method of analysis for solid state sensors resulting in the development of a "transduction path diagram". This diagram is capable of illustrating the operation of an existing sensor as well as allowing the systematic investigation of sensor configurations. Several phases were required in the development of this method.

The first phase required the identification and categorization by energy form of sensor measurands. The results of this process are presented in Chapter III. The second phase required the identification of known transduction and modification principles drawn from all fields of science. These are presented as fundamental building blocks of the transduction path and are cross-indexed by measurand in Chapter IV and Appendices I through O. The third phase required the development of a structure which would systematically interconnect all of the trandsduction and modification principles identified. The "transduction path diagram" described in Chapter V was proposed as such a structure. In order to test it, information was collected on 108 classes of sensors from literature sources and commercial suppliers. The transduction path of each sensor was then determined and examined for compatibility with the transduction path diagram. Representative results are presented in Chapter V. In the fourth phase, sensor configurations were systematically investigated using the transduction path method. Conclusions and an overview of the method are presented in Chapter VI.

III. MEASURANDS

A. CLASSIFICATION OF MEASURANDS

In order to adequately describe the various transduction and modification steps that may be utilized in transducers, it is necessary to identify the measurands involved. The measurand of a sensor contains information about an aspect of the physical world that is the object of measurement. This information is carried by a signal which is manifested as some form of energy. Seven forms of energy have been identified which are sufficient to describe the signals bearing information about the measurand. These are mechanical, thermal, electrical, magnetic, optical, chemical, and nuclear forms of energy.

The electrical, magnetic, optical and nuclear forms of energy are all related by the laws of electromagnetic theory. Electrical and magnetic phenomena fall at the DC and low frequency end of the electromagnetic spectrum. Optical phenomena fall within a higher frequency range of the electromagnetic spectrum, ranging from infrared through ultraviolet. Nuclear phenomena lie at the high end of the electromagnetic spectrum and represent the most energetic of the electromagnetic waves. Mechanical phenomena generally represent an ordered form of energy on a macroscopic scale, while thermal phenomena represent a disordered form of energy on a submicroscopic scale. Chemical phenomena rely upon the principles of interatomic bonding and sharing of electrons to explain their behavior.

Common to all of these phenomena is the idea that a signal containing information is available in one of the seven forms of energy. For instance, pressure is a physical quantity that commonly is the subject of measurement. It may be represented as a time-varying signal belonging to the mechanical form of energy. Likewise, light intensity is a physical quantity that may be represented as a time-varying signal belonging to the optical form of energy.

The physical quantities associated with the transduction and modification principles identified in the next chapter are listed in Tables I through VIII. These particular physical quantities, or measurands, have been found to figure prominently in the sensors and transducers available today. In order to mathematically express these measurands, an international system (SI) of measurement was developed. The six basic units of the SI measurement system are length, mass, time, current, temperature, and luminous intensity. These basic units have been adequately described in the literature and are simply mentioned here. Furthermore, these six basic units are sufficient to describe all of the measurands belonging to the seven forms of energy. Complete listings of physical quantities associated with each form of energy are attached as Appendices A through G. The particular physical quantities which serve as measurands for the transduction and modification principles are capitalized in these appendices. The non-capitalized entries are provided in the interest of completeness.

1. Mechanical Measurands

Identification of mechanical measurands may be guided by the following definitions. Mechanical energy is the sum of kinetic energy and potential energy. Kinetic energy is referred to as the energy of motion while potential energy is referred to as the energy of position. The process by which the kinetic or potential energy is changed is called work. Kinetic energy, potential energy, and work are all relevant to the physics of macroscopic mechanics. In general, a measurand may be classified as a mechanical measurand if the physics of macroscopic mechanics apply.

In many cases, it is possible to mathematically express one measurand in terms of a different, but related, measurand. For example, velocity is the first derivative of position and acceleration is the first derivative of velocity.

The physical quantities serving as mechanical measurands for the transduction and modification principles of the next chapter are listed in Tables I and II. For a complete listing, see Appendix A.

2. Thermal Measurands

The thermal measurands deal with a form of energy that is disordered, or random in nature. It is associated with the submicroscopic behavior of atoms and molecules of a system. The manner in which energy is transferred in thermal systems is known as heat, which is a form of work. The most commonly used measurand in the thermal domain is temperature. It is a measure of the random kinetic energy of the atoms and molecules in a system. In many cases, it is possible to mathematically express one measurand in terms of a different, but related, measurand. For example, the field of thermodynamics contains many equations pertaining to the transfer of thermal energy.

The physical quantities serving as thermal measurands for the transduction and modification principles of the next chapter are listed in Table III. For a complete listing, see Appendix B.

3. Electrical Measurands

The electrical measurands lie at the DC or low end of the electromagnetic spectrum. The concepts of charge and

TABLE I

Mechanical Measurands I

- ACCELERATION
- ACOUSTIC ENERGY
- ACOUSTIC WAVE
- ANGLE
- ATTRACTION, MAGNETIC
- CONTRACTION, LATERAL
- DEFLECTION
- DEFORMATION
- DENSITY
- DIAMETER, CONDUCTOR
- DIAMETER, WIRE
- DIMENSION
- DIPOLE ALIGNMENT
- DIRECTION OF MOTION
- DISPLACEMENT
- ELASTIC PROPERTIES
- FLOW
- FLOW, FLUID
- FLOW RATE, MASS
- FORCE
- FREQUENCY, ACOUSTIC
- FREQUENCY, MECHANICAL
- FREQUENCY, RESONANT
- FREQUENCY, FLEXURAL
- FREQUENCY, TORSIONAL
- FRICTION
- FRICTION, LIQUID
- FRICTION, SOLID
- HARDNESS
- IMMERSION, PARTICLE
- INCLINATION
- LENGTH
- LEVEL, LIQUID

charge carriers are closely related to most of the measurands associated with electricity. These measurands may describe the charge itself, or they may describe the external factors which determine the behavior of charge. For instance, the physical quantity of resistance affects the manner in which charge propagates through a material giving rise to current. Once again, it is possible to mathematically express many of the electrical measurands in terms of other electrical measurands. A particularly well known example of this is Ohm's Law.

TABLE II

Mechanical Measurands II

MICROBENDS
MOMENTUM, ANGULAR
MOVEMENT, AIR
MOVEMENT, POLAR FLUID
PATH LENGTH DIFFERENCE
POSITION
POSITION, ANGULAR
PRESSURE
PRESSURE, SOUND
PRESTRAIN
PROXIMITY
PROXIMITY, CONDUCTOR
ROTATION
SAW
SEPARATED GASES
SHAPE
SHOCK
SOUND
STRAIN
STRAIN, LOCALIZED
STRESS
STRESS, LONGITUDINAL
TENSION
TENSION, SURFACE
THICKNESS
TORQUE
ULTRASONIC
VELOCITY
VELOCITY, ANGULAR
VELOCITY, AIR
VELOCITY, FLOW
VELOCITY, SAW
VIBRATION
VOLUME
WAVELENGTH

The physical quantities serving as electrical measurands for the transduction and modification principles of the next chapter are listed in Table IV. For a complete listing, see Appendix C.

4. Magnetic Measurands

The magnetic measurands, like the electrical measurands, lie at the DC or low end of the electromagnetic spectrum. Magnetic phenomena, by definition, result from

TABLE III

Thermal Measurands

CONDUCTIVITY, THERMAL
HEAT
HEAT FLUX
HEAT TRANSFER RATE
POINT, BOILING
POINT, FREEZING
TEMPERATURE
TEMPERATURE CHANGE
TEMPERATURE, COOLING
TEMPERATURE DIFFERENCE
TEMPERATURE GRADIENT
TEMPERATURE, NOISE

charge in motion. Electromagnetic theory is that body of knowledge which binds the electric and magnetic phenomena together. It is a well known fact that electricity and magnetism are closely related and easily converted from one form to another. For example, an electric generator relies upon both electric and magnetic principles for its operation. The relations are well understood and readily available in equation form.

The physical quantities serving as magnetic measurands for the transduction and modification principles of the next chapter are listed in Table V. For a complete listing, see Appendix D.

5. Optical Measurands

The optical measurands are associated with those electromagnetic phenomena which occur in the range of infrared to ultraviolet. Unlike the low end of the spectrum, few attempts are made to consider the orthogonal electric and magnetic components separately. These measurands attempt to describe the factors that affect the

TABLE IV

Electrical Measurands

CAPACITANCE
CHARGE
CHARGE CARRIER
CHARGE LOSS
CONDUCTIVITY
CORONA DISCHARGE
CURRENT
CURRENT, RESTORING
CURRENT, VACUUM
DIELECTRIC CONSTANT
ELECTRIC FIELD
ELECTRIC FIELD, AC
ELECTRONS
EMF
EMF, AC
EMF, DC
EMF, FM
EMF, GATE
FREQUENCY, DIFFERENCE
FREQUENCY, ELECTRIC
FREQUENCY, ELECTROMAGNETIC
FREQUENCY, RESONANT
IMPEDANCE
INDUCTANCE
IONIZATION
POWER
RADIATION, ELECTROMAGNETIC
RESISTANCE
RESISTANCE, GATE
RESISTIVITY
SPARK, ELECTRICAL
THERMORESISTANCE
VOLTAGE
WAVE, ELECTROMAGNETIC

propagation and behavior of optical energy. For instance, reflectivity at an air-fiber interface determines the amount of light which may be coupled into an optical fiber. This is particularly important when designing an optical communications link and calculating the optical power budget. The field of optics has many such relations readily available in equation form.

The physical quantities serving as optical measurands for the transduction and modification principles

TABLE V

Magnetic Measurands

FLUX, CHANGE
FLUX DENSITY
FREQUENCY, ELECTROMAGNETIC
MAGNETIC FIELD
MAGNETIC FIELD, DYNAMIC
MAGNETIC FIELD INTENSITY
MAGNETIC FIELD, STATIC
MAGNETIC INDUCTION
MAGNETIZATION
MAGNETIZATION DIRECTION
MAGNETIZATION, SUDDEN
PARAMAGNETISM
PERMEABILITY
RADIATION, ELECTROMAGNETIC
WAVE, ELECTROMAGNETIC

of the next chapter are listed in Table VI. For a complete listing, see Appendix E.

6. Chemical Measurands

The chemical measurands are associated with the manner in which atoms and molecules share electrons, or bond together. A field of science that is well understood has built up around this molecular bonding. The applications in solid state sensor technology have not been developed very far, however, due to the lack of suitable device configurations. Once again, it is possible to mathematically express one measurand in terms of a different, but related, measurand. Chemistry has many such relations available in equation form. In this particular case, however, the formula is often expressed in chemical symbols rather than conventional mathematical symbols.

The physical quantities serving as chemical measurands for the transduction and modification principles of the next chapter are listed in Table VII. For a complete listing, see Appendix F.

TABLE VI

Optical Measurands

ABSORPTANCE
COLOR, ANY
COLOR, PRIMARY
COUPLING COEFFICIENT
FREQUENCY, OPTICAL
ILLUMINATION
ILLUMINATION, DIFFERENCE
IMAGE, DECEPTIVE
IMAGE, OPTICAL
INFRARED RADIATION
LIGHT
LIGHT EMISSION
MAX ENERGY WAVELENGTH
MAX POLARIZED LIGHT
OPAQUENESS
OPTICAL COUPLING
OPTICAL POWER
PHASE DIFFERENCE
POLARIZATION
POLARIZING ANGLE
RADIANT HEAT
REFLECTION COEFFICIENT
REFLECTIVITY
REFRACTIVE INDEX
SPECTRAL LINE SEPARATION
TRANSMISSIVITY
ULTRAVIOLET LIGHT
VISIBLE LIGHT

7. Nuclear Measurands

The nuclear measurands deal with phenomena that lie at the high end of the electromagnetic spectrum. Of particular interest in this area is the ability to detect the presence of ionizing radiation. This has many applications in the fields of nuclear physics, spacecraft design, medicine, and nuclear power. Many nuclear equations are available to describe particular events and effects. Perhaps the most famous of these equations is the one developed by Einstein relating mass, energy, and the velocity of light.

TABLE VII

Chemical Measurands

BIOLOGICAL MECHANISM
CHEMICAL COMPOSITION
CHEMICAL REACTION
CHEMICAL REACTION RATE
CHEMICAL STATE
CHEMICAL CONCENTRATION
CONCENTRATION, GAS
CONCENTRATION, IONIC
CONCENTRATION, NO
CONCENTRATION, OXYGEN
CONCENTRATION, SALT
CONCENTRATION, VAPOR
CRYSTALLIZATION
DIFFUSION RATE
GAS, SAMPLE
HUMIDITY
OXIDATION
SOLUBILITY, GAS

The physical quantities serving as nuclear measurands for the transduction and modification principles of the next chapter are listed in Table VIII. For a complete listing, see Appendix G.

TABLE VIII

Nuclear Measurands

BOMBARDMENT, NUCLEAR
FREQUENCY, ELECTROMAGNETIC
RADIATION, GAMMA RAY
RADIATION, IONIZING
RADIATION, NUCLEAR
RADIATION, X-RAY

IV. TRANSDUCTION AND MODIFICATION ELEMENTS

A. THE TRANSDUCTION MATRIX

Transduction is the process by which one form of energy is converted into another form of energy. Likewise, modification is the process by which one form of energy is changed to a like form of energy. In this section, the known transduction and modification principles are identified. These principles are the transduction and modification elements which make up the transduction path of a solid state sensor.

One way to represent these transduction and modification elements is in matrix form. A symmetric 7 X 7 matrix with rows and columns corresponding to the seven forms of energy is sufficient to illustrate all possible transduction and modification elements. The rows of the matrix represent the energy form of the input measurand while the columns represent the energy form of the output measurand. Since the matrix is symmetric, the diagonal blocks represent modification elements as the output energy form is the same as the input energy form. Likewise, the off-diagonal blocks represent transduction elements as the output energy form is different from the input energy form. The transduction matrix is illustrated in Figure 4.1. In the next chapter, the elements of this matrix will form the basis of the transduction path method of analysis, resulting in the development of the "transduction path diagram".

B. THE MATRIX ELEMENTS

The transduction matrix in Figure 4.1 serves to show how the transduction and modification elements may be organized

OUTPUT

INPUT

	NUCL	CHEM	OPTI	MAGN	THER	MECH	ELEC
NUCL							
CHEM							
OPTI							
MAGN							
THER							
MECH							
ELEC							

Figure 4.1 Transduction Matrix.

into a single structure. To show the detailed structure of the matrix, it is broken up into a series of tables, each listing the transduction and modification principles with a particular form of energy as the output. The first column of the table represents the energy form of the input measurand and ranges from nuclear through electrical. The last column of the table represents the energy form of the output measurand and does not change within the table. In this manner, the table may be regarded as representing a column of the matrix in Figure 4.1.

In order to change from one energy form to another, it is necessary to employ some transduction or modification principle. The middle column of each table lists the transduction or modification principles that may be employed to make the designated change. For example, Table IX, entitled "Mechanical Output Elements", contains an entry in which the input energy form is magnetic and the output energy form is mechanical. The transduction principle that makes this transition possible is magnetostriction, so an entry to that effect is made in the middle column of the table.

The other entries in the tables are prepared in a similar manner. Where a particular transduction or modification principle cannot be conveniently specified, the device performing the transduction or modification is specified instead. For example, a bridge circuit is commonly used as an electrical modifier in solid state sensors. Its operation is based upon several electronic principles, but there is little to gain by enumerating them separately. It is sufficient to know that a structure exists which will convert small changes in resistance to a usable voltage and is called a "Bridge Circuit". The reader, upon seeing such an entry, would then refer to the appropriate literature for a full description of the operation and theory of such a device.

No attempt is made in this paper to describe the theory behind the transduction and modification steps employed in the transduction path approach to solid state sensors. Of prime importance in this paper is to convey a method by which solid state sensors may be analyzed and investigated. However, to make it easier for the reader to utilize this method, an index of all the transduction and modification principles is provided in Appendix H. Each principle is listed alphabetically, along with the associated input and output measurands. Additionally, an appropriate source for detailed information is indicated for each principle. Unless otherwise indicated, the source which may be consulted for further information on each principle is [Ref. 11].

1. Mechanical Output Elements

In this section, the transduction and modification principles which have a mechanical output measurand are identified. Table IX contains a listing of those transduction and modification principles which represent blocks in the mechanical output column of the transduction matrix. By definition, those entries in Table IX with a mechanical input measurand are modification elements while all others are transduction elements. The modification elements do not change the energy form of the input measurand; in this case it remains in mechanical form. Rather than listing all of the known mechanical modifiers, only those with known applications in solid state sensors are included in Table IX.

A mechanical modification element that is utilized in many solid state sensors is "elastic deformation". This is a general term that may be applied to any structure or device that relies upon its elastic properties to modify mechanical energy. A common example of a device that utilizes this principle is a diaphragm which deforms in a predictable manner as a function of pressure. Many pressure transducers operate on this principle.

In the traditional generation of sensors, the elastic properties of metal were often relied upon for applications requiring elastic deformation. However, many such metal devices were subject to hysteresis in which the prestressed behavior differed from the non-prestressed behavior. As noted earlier, silicon has proved to be a nearly ideal material for constructing solid state sensors. Being a monolithic material, silicon is very nearly free from the disadvantages of hysteresis. Furthermore, silicon is capable of being micromachined into various configurations through the process of chemical etching. Micromachining is the process by which extremely small structures may be fabricated and represents a great reduction in scale from the traditional generation of sensors which employed macromachining.

Since the ultimate goal of a solid state sensor is to convert a measurand into an electrical form of energy, the transduction and modification elements listed in Table IX represent only an intermediate step in the transduction path of a sensor. Further transduction would be necessary to finally arrive at a useful electrical output. As can be seen in Table IX, there are often several principles that may be utilized to transform a given form of energy into a mechanical form. In order to determine which of the transduction or modification elements may be useful for a particular application, the reader may refer to Appendix N for information on input and output measurands.

2. Thermal Output Elements

In this section, the transduction and modification principles which have a thermal output measurand are identified. Table X contains a listing of those transduction and modification principles which represent blocks in the thermal output column of the transduction matrix. By definition, those entries in Table X with a thermal input measurand are modification elements while all others are transduction elements. The modification elements do not change the energy form of the input measurand; in this case it remains in thermal form.

TABLE IX

Mechanical Output Elements

INPUT FORM	PRINCIPLE	OUTPUT FORM
Nuclear *		* Mechanical
Chemical *	Atmolysis Capillary Column Chemisorption Jones Effect Osmosis Paramagnetism	* Mechanical
Optical *	Radiation Pressure	* Mechanical
Magnetic *	Einstein-de Hass Effect Magnetic Anisotropy Magnetic Sound Dispersion Magnetostriction	* Mechanical
Thermal *	Thermal Expansion	* Mechanical
Mechanical *	Acoustic Interference Acoustic Propagation Archimede's Principle Bauschinger Effect Cavitation Doppler (Acoustic) Elastic Deformation Elastic Limit Eotvos Effect Gravity Pendulum Hydrodynamic Element Lorentz Contraction Mechanical Resonance Poisson's Ratio Quartz Resonator Resonance Rotor Vibrating Wire Vortex Shedding	* Mechanical
Electrical *	Ampere's Law Electric Wind Effect Electroacoustic Electrocapillarity Electro-osmosis Electrostrictive Ferroelectric Interdigital Transducer Johnsen-Rahbek Effect Pinch Effect Winslow Effect	* Mechanical

An element of the matrix that is particularly useful is that of "thermal conductivity". In existing sensors, this principle is used to measure air velocity, mass flow rate, flow velocity, chemical composition, and heat transfer rate. It relies upon the concept of heat energy transfer. Several physical phenomena have an effect upon the manner in which heat is transferred and can thus be indirectly measured. For example, a solid state anemometer has been developed which operates by measuring the temperature of a heated element in contact with the airflow. The amount of heat that is transferred from the heated element to the airstream is dependent upon the thermal conductivity of air and the velocity of the airflow. Since the mathematical relationships are known, the air velocity may be calculated in an appropriate manner.

The transduction and modification elements listed in Table X represent only an intermediate step in the transduction path of a sensor since the output is not electrical in form. Further transduction would be necessary to finally arrive at a useful electrical output. As can be seen in Table X, there are often several principles that may be utilized to transform a given form of energy into thermal energy. In order to determine which of the transduction or modification elements may be useful for a particular application, the reader may refer to Appendix M for information on input and output measurands.

3. Electrical Output Elements

In this section, the transduction and modification principles which have an electrical output measurand are identified. Tables XI and XII contain listings of those transduction and modification principles which represent blocks in the electrical output column of the transduction matrix. This table is unique in that the output measurand

TABLE X

Thermal Output Elements

INPUT FORM		PRINCIPLE		OUTPUT FORM
Nuclear	*	Fission	*	Thermal
Chemical	*	Combustion Electrolytic Dissociation Photoabsorption Thermal Conductivity	*	Thermal
Optical	*	Photoabsorption	*	Thermal
Magnetic	*	Thermomagnetic	*	Thermal
Thermal	*	Fourier's Law Righi-Leduc Effect Thermal Conductivity	*	Thermal
Mechanical	*	Craft's Rule Hot Wire Piezocaloric Thermal Conductivity	*	Thermal
Electrical	*	Benedick Effect Ettingshausen Effect Joule's Law Peltier Effect Spark Gap	*	Thermal

is of a form suitable for output by a solid state sensor. These transduction and modification steps represent the final stage in a transduction path which must terminate in the electrical domain. By definition, those entries in Tables XI and XII with an electrical input measurand are modification elements while all others are transduction elements.

The electrical input measurand elements of Table XII do not change the form of energy from input to output. These are the modification elements, commonly referred to as signal processing steps. The entire field of electronics may be considered to lie within the realm of electrical modifiers. Rather than attempt to list them all within this section, only those devices which have found particular applications in the field of solid state sensors are included.

Those entries in Tables XI and XII which are not modifiers are, of course, transduction elements. These are particularly useful for use in solid state sensors in that they represent a direct path to the electrical domain from a non-electrical measurand. They also serve as the terminal step in a transduction path which may utilize several transduction or modification elements as intermediate steps. By playing such an important role in the transduction path, these transduction and modification elements form the most important column in the transduction matrix.

As can be seen in Tables XI and XII, there are many transduction and modification principles which have an electrical output. This allows great flexibility in choosing the principles to be used in the design of a solid state sensor. However, only a few principles prove useful in a given application, so the reader is referred to Appendix O for information on input and output measurands.

4. Magnetic Output Elements

In this section, the transduction and modification principles which have a magnetic output measurand are identified. Table XIII contains a listing of those transduction and modification principles which represent blocks in the magnetic output column of the transduction matrix. By definition, those entries in Table XIII with a magnetic input measurand are modification elements while all others are transduction elements. The modification elements do not change the energy form of the input measurand; in

TABLE XI

Electrical Output Elements I

INPUT FORM		PRINCIPLE	OUTPUT FORM
Nuclear	*	Fission Joshi Effect Photoconductive Photoemissive Photovoltaic PIN Photocurrent	* Electrical
Chemical	*	Cathodic Reduction Chemisorption Electrochemical Gate Controlled Diode Hygroscopic Salt ISFET Kohlrausch's Law Polymer PAPA Triboelectricity Variable Dielectric Zirconium Oxide Cell	* Electrical
Optical	*	APD Becquerel Effect CCD Hallwock's Effect Hertz Effect Josephson Junction Photoconductance Photoemissive Photovoltaic PIN Photocurrent	* Electrical
Magnetic	*	Corbino Effect Faraday Induction Galvanomagnetic (Hall) Gauss Effect Josephson Junction Magnetoresistance Sensing Coil Variable Permeability	* Electrical
Thermal	*	Edison Effect Josephson Junction Mattheissen's Rule Nernst Effect PTAT Pyroelectric TCD Thermoconductance Thermoelectric (Seebeck) Thermoresistance Thermovoltaic Junction Variable Dielectric Workman-Reynolds Effect	* Electrical

this case it remains in magnetic form. Relatively few principles with a magnetic output are known. However, most of these are transduction principles with the most common input energy form being mechanical.

Two magnetic modification elements are listed in Table XIII and the rest are transduction elements. Since the ultimate goal of a solid state sensor is to convert a measurand into an electrical form of energy, the transduction and modification elements listed in Table IX represent only an intermediate step in the transduction path of a sensor. Some other transduction element must follow in the transduction path if an electrical output is to be realized. Table XI contains six transduction principles which lead from a magnetic input to an electrical output. These represent six possible paths which may lead from a magnetic signal to a useful electrical signal. As will be illustrated in a subsequent chapter, many other possible paths exist as well.

The magnetic output principles are currently being used quite heavily in the field of automotive engine control sensors. Most use has been made of the Wiegand Effect and the Inductive Eddy Current Effect in this field. Another very useful principle is magnetostriction, which converts a mechanical strain into a magnetic field. Magnetostriction is also capable of converting a magnetic field into a mechanical strain. For this reason, magnetostriction appears in Table IX as well. Several other effects also exhibit this property of being reversible.

As can be seen in Table XIII, sometimes there are several principles which may be utilized to transform a given form of energy into magnetic energy. In order to determine which of the transduction or modification elements may be useful for a particular application, the reader may refer to Appendix L for information on input and output measurands.

TABLE XII

Electrical Output Elements II

INPUT FORM	PRINCIPLE	OUTPUT FORM
Mechanical *	Acoustoelectric	* Electrical
	Conductive Elastomer	
	Doppler (Electric)	
	Dorn Effect (Electrokinetic)	
	Interdigital Transducer	
	Ion Movement	
	Mechanical Switch	
	Oscillator	
	Piezoelectric	
	Piezo-optical Effect	
	Piezoresistance	
	PN Piezojunction	
	Potentiometric	
	Proximity Effect	
	Resistance-Pressure Effect	
	Thermoelastic Effect	
	Variable Conductivity	
	Variable Dielectric	
	Variable Reluctance	
	Wertheim Effect	
Electrical *	Bridge Circuit	* Electrical
	Capacitive PI-FET	
	CFT	
	Charge Amplifier	
	Charge Mobility	
	Differential Transformer	
	ECKO	
	ECOLD	
	Electro-optical Effect	
	Gate Controlled Diode	
	Impedance	
	Induction	
	ISFET	
	Josephson Junction	
	MOS Capacitor	
	Ohm's Law	
	Oscillator	
	Phase Shift Oscillator	
	PIN	
	PLL	
	Power Law	
	Quantum Interferometer	
	Sensing Coil	
	Signal Processing	
	Spark Gap (Paschen's Law)	
	Unijunction Oscillator	
	Varistor	
	Wien Effect	
	Zener Effect	

TABLE XIII

Magnetic Output Elements

INPUT FORM		PRINCIPLE	OUTPUT FORM
Nuclear	*	Fission	* Magnetic
Chemical	*		* Magnetic
Optical	*	Photomagnetic Effect	* Magnetic
Magnetic	*	Barkhausen Effect Wiegand Effect	* Magnetic
Thermal	*	Curie-Weiss Law	* Magnetic
Mechanical	*	Barnett Effect Doppler (Magnetic) Flux Density Inductive Eddy Current Magnetostriction Villari Effect	* Magnetic
Electrical	*	Faraday Induction	* Magnetic

5. Optical Output Elements

In this section, the transduction and modification principles which have an optical output measurand are identified. Tables XIV and XV contain listings of those transduction and modification principles which represent blocks in the optical output column of the transduction matrix. By definition, those entries in Tables XIV and XV with an optical input measurand are modification elements while all others are transduction elements. The modification elements do not change the energy form of the input measurand; in this case it remains in optical form. The entire field of optics may be considered to lie within the realm of optical modifiers. Rather than attempting to list all of the known optical modifiers, only those with known applications in solid state sensors are included in Table XIV.

Many transduction and modification principles are known which have an optical output. One of the optical modifiers which is finding increasing application in the field of solid state sensors is the optical fiber. Since the wavelength of light is on the order of micrometers, it can be used to measure very small physical changes with good resolution. Extremely sensitive detectors have been developed which make possible the detection of very small changes in the light propagation characteristics of an optical fiber. Furthermore, advances in materials processing have led to optical fibers of unprecedented uniformity and purity. These factors combine to make optical fibers excellent distributed sensing elements of great sensitivity. Already, they have seen use in magnetometers and optical gyroscopes.

The development of the laser has likewise had a large impact on the field of solid state sensors. A laser resonant cavity is extremely sensitive to changes in physical dimension and as such makes a good sensing element with extremely good resolution. The development of the laser diode has likewise opened new possibilities for optical systems in solid state sensing. Small and reliable, they bring optics into the solid state age.

Since the ultimate goal of a solid state sensor is to convert a measurand into an electrical form of energy, the transduction and modification elements listed in Tables XIV and XV represent only an intermediate step in the transduction path of a sensor. Further transduction would be necessary to finally arrive at a useful electrical output. A fairly wide choice of optical principles with an electrical output are available in Tables XIV and XV. In order to determine which of the transduction or modification elements may be useful for a particular application, the reader may refer to Appendix K for information on input and output measurands.

TABLE XIV

Optical Output Elements I

INPUT FORM		PRINCIPLE		OUTPUT FORM
Nuclear	*	Cerenkov Effect	*	Optical
		Fission		
		Geiger Effect		
		Luminescence		
		Radiation Darkening		
Chemical	*	Absorption (Lambert)	*	Optical
		Bioluminescence		
		Combustion		
		Crystalluminescence		
		Lambert's Law		
		Optical Rotation		
		Variable Density		
Optical	*	Amplitude Modulation	*	Optical
		Brewster's Law		
		Christiansen Effect		
		Color Mixing		
		Lens System		
		Luminescence		
		NTIR		
		Phase Interferometer		
		Photoluminescence		
		Snell's Law		
		Variable Reflectivity		
Magnetic	*	Faraday Rotation	*	Optical
		Kerr Magneto-optic Effect		
		Liquid Crystal		
		Luminescence		

TABLE XV

Optical Output Elements II

INPUT FORM	PRINCIPLE	OUTPUT FORM
Thermal *	Blackbody Radiation	* Optical
	Energy Bandgap Shift	
	Gladstone & Dale's Law	
	Incandescence	
	Liquid Crystal	
	Mirage Effect	
	Stefan-Boltzmann Law	
	Thermo-optic	
	Wien's Displacement Law	
Mechanical *	Absorption	* Optical
	Coulomb's Law	
	Diffraction	
	Doppler (Optical)	
	Elasto-optic Effect	
	Evanescence	
	FTIR	
	Gladstone & Dale's Law	
	Interference Coating	
	Lambert's Cosine Law	
	Lambert's Law	
	Laser External Mirror	
	Numerical Aperture	
	Optical Interference	
	Photoelastic Effect	
	Piezo-optical Effect	
	Radiative Losses	
	Sagnac Phase Shift	
	Schlieren Grating	
	Sonoluminescence	
	Triboluminescence	
	Variable Birefringence	
	Variable Opacity	
	Variable Refractive Index	
Electrical *	Cerenkov Effect	* Optical
	Electroluminescence	
	Electro-optical Effect	
	Kerr Effect	
	LED Electro-optic	
	Luminescence	
	Stark Effect	

6. Chemical Output Elements

In this section, the transduction and modification principles are identified which yield a chemical output measurand. Table XVI contains a listing of those transduction and modification principles which represent blocks in the chemical output column of the transduction matrix. By definition, those entries in Table XVI with a chemical input measurand are modification elements while all others are transduction elements. The modification elements do not change the energy form of the input measurand; in this case it remains in chemical form. Most of the field of chemistry may be considered to lie within the realm of chemical modifiers. Rather than attempting to list all of the known chemical modifiers or chemical reactions, only those with known applications in solid state sensors are included in Table XVI.

The principles of modern chemistry that have seen implementation in solid state sensors are relatively few in number considering the vast bulk of knowledge available on chemical processes. Chemical sensors are exposed an environment that is often damaging to associated integrated circuitry. For this reason, the problem of sensor sealing has received a great deal of attention. The ideal solid state chemical sensor would have a sensing element fully exposed to the chemical reaction undergoing measurement while still providing protection to the delicate electronic circuitry.

Since the ultimate goal of a solid state sensor is to convert a measurand into an electrical form of energy, the transduction and modification elements listed in Table XVI represent only an intermediate step in the transduction path of a sensor. Further transduction would be necessary to finally arrive at a useful electrical output. For example, the photochemical processes employed in black and white photography convert an optical image into a chemical reaction on the photographic film. The information stored in the chemical state of the film is not immediately useful as an output since it is not electrical in nature. The chemical state is, however, available as an optical signal since the chemical state determines the opacity of the film. This optical signal may then be converted into an electrical signal through an appropriate application of a photoelectric effect.

As can be seen in Table XVI, there is occasionally more than one principle that may be utilized to transform a given form of energy into chemical energy. Therefore, the reader is referred to Appendix J for information on input and output measurands.

TABLE XVI

Chemical Output Elements

INPUT FORM		PRINCIPLE		OUTPUT FORM
Nuclear	*		*	Chemical
Chemical	*	Adsorption Donnan Membrane Equilibrium	*	Chemical
Optical	*	Photochemical Photosynthesis	*	Chemical
Magnetic	*		*	Chemical
Thermal	*	Arrhenius Equation Henry's Law	*	Chemical
Mechanical	*		*	Chemical
Electrical	*	Electroplating	*	Chemical

7. Nuclear Output Elements

In this section, the transduction and modification principles which have a nuclear output measurand are identified. Table XVII contains a listing of those transduction and modification principles which represent blocks in the nuclear output column of the transduction matrix. By definition, those entries in Table XVII with a nuclear input measurand are modification elements while all others are transduction elements. The modification elements do not change the energy form of the input measurand; in this case it remains in nuclear form.

The field of nuclear physics has long been a very specialized field with very specialized instrumentation. However, the demand for low cost, reliable sensing devices has grown in recent years. Spacecraft designers, physicists, the nuclear industry, medical researchers, and the military represent a growing number of users with applications for such devices.

Since the ultimate goal of a solid state sensor is to convert a measurand into an electrical form of energy, the transduction and modification elements listed in Table XVII represent only an intermediate step in the transduction path of a sensor. Further transduction would be necessary to finally arrive at a useful electrical output. It can be seen in Table XVII that the number of useful principles with a nuclear output is rather small. However, due to the particularly energetic and dangerous qualities of nuclear output measurands, it is unlikely that the principles listed in Table XVII will see widespread application. In order to determine which of the transduction or modification elements may be useful for a particular application, however, the reader may refer to Appendix I for information on input and output measurands.

TABLE XVII

Nuclear Output Elements

INPUT FORM		PRINCIPLE		OUTPUT FORM
Nuclear	*	Fission	*	Nuclear
Chemical	*		*	Nuclear
Optical	*		*	Nuclear
Magnetic	*		*	Nuclear
Thermal	*		*	Nuclear
Mechanical	*	Doppler (Nuclear)	*	Nuclear
Electrical	*	Bremstrahlung Radiation	*	Nuclear

V. THE TRANSDUCTION PATH METHOD

A. DESCRIPTION

The purpose of a solid state sensor is to convert an input measurand to an electrical output signal. The input measurand is manifested as a signal belonging to one of seven different forms of energy. When this signal is other than electrical in nature, it must undergo the process of transduction before it can be processed by electronic devices.

This process of transduction may be described through what is now referred to as the "transduction path" method. The method defines a transduction path as a sequence of individual transduction or modification principles which lead from an input measurand to an electrical output signal. While some transducers employ only a single transduction or modification principle, many transducers are multi-step devices which employ several principles for their operation.

For example, a typical pressure transducer is a two step device which utilizes the principles of elastic deformation and piezoresistance. Elastic deformation modifies the mechanical input measurand, pressure, into a mechanical output measurand, strain. This strain is in turn applied as a mechanical input measurand to a piezoresistive device which transduces it to a change in electrical resistance. The transduction path of this sensor would consist of a modification principle, elastic deformation, followed by a transduction principle, piezoresistance.

An example of a single step device is the thermocouple. It operates on the thermoelectric effect and transduces a thermal input measurand, temperature, directly to an electrical output signal, voltage. The transduction path of this sensor would consist of only a single transduction principle, the thermoelectric effect.

As can be seen in the preceding examples, the transduction path may consist of one or more discrete transduction or modification steps. A requirement in all cases, however, is that the final step of the transduction path must yield an electrical output measurand. Also, in a multiple step transduction path, the output and input measurands of consecutive steps must be the same.

The transduction path method represents a means of describing the operation of a solid state sensor. However, it requires knowledge of transduction and modification principles drawn from all fields of science. It is for this reason that the known transduction and modification principles are tabulated in Appendix H for easy reference.

The transduction matrix of Figure 4.1 represents a means through which transduction and modification principles may be grouped in an orderly fashion. Each block represents a family of either transduction or modification principles with associated input and output energy forms. Blocks on the diagonal are modification elements while blocks off the diagonal are transduction elements.

In Chapter IV, the known transduction and modification principles were identified by family in Tables IX through XVII. The number of principles belonging to each family, based on input-output energy forms, is annotated in Figure 5.1. The number in each block represents the number of known principles which make that particular energy transduction or modification possible. For example, Table XI contains ten principles which permit the transduction of optical energy to electrical energy. Accordingly, a 10 is entered in the block of Figure 5.1 which lies at the intersection of the optical input row and the electrical output column. Empty blocks in Figure 5.1 indicate that no principle is known which permits that particular transduction or modification of energy.

OUTPUT

INPUT	NUCL	CHEM	OPTI	MAGN	THER	MECH	ELEC
NUCL	1		5	1	1		6
CHEM		2	7		4	6	11
OPTI		2	11	1	1	1	10
MAGN			4	2	1	4	8
THER		2	9	1	3	1	13
MECH	1		24	6	4	19	20
ELEC	1	1	7	1	5	11	28

Figure 5.1 Distribution of Principles.

The transduction path method represents a general concept which may be utilized to describe the operation of a solid state sensor. However, a framework is necessary if the method is to be utilized effectively. As will be seen in the next section, the "transduction path diagram" provides just such a framework.

B. THE TRANSDUCTION PATH DIAGRAM

Conceptually, the transduction path of a sensor consists of a sequence of individual transduction or modification principles which lead from an input measurand to an electrical output signal. In this section, a structure is developed which is able to present the transduction path of a solid state sensor in graphical form.

Representing a refinement of the transduction matrix introduced in Chapter IV, the structure shown in Figure 5.2 has several important properties. Most important of these properties is that this structure, hereafter referred to as the "transduction path diagram", is capable of providing a graphical illustration of a transduction path. This diagram interconnects all of the known transduction and modification principles in a systematic and orderly fashion. It is capable of not only describing the operation of existing sensors, but may also serve to illustrate how a sensor can be susceptible to undesirable, secondary measurands that may inhibit its accuracy. Finally, it may also serve as a mechanism for the systematic investigation of sensor configurations.

At first glance, the diagram appears similar to the transduction matrix introduced in Chapter IV. Both are arranged about a symmetric 7 X 7 matrix with energy form labels on the rows and columns. Similarity to the transduction matrix ends at this point, however. In the transduction matrix, the rows represented the input energy form and the columns represented the output energy form. However, in the transduction path diagram, a different approach is taken. The input/output distinction is made in

		INPUT							
		NUCL	CHEM	OPTI	MAGN	THER	MECH	ELEC	
INPUT	NUCL								OUTPUT
	CHEM								
	OPTI								
	MAGN								
	THER								
	MECH								
	ELEC								
		OUTPUT							

Figure 5.2 Transduction Path Diagram.

an entirely different manner as will be explained later in this section.

In order to show how the transduction path diagram operates, it is best broken down into three main sections. These are the input section, the transduction path section, and the output section.

1. Input Section

On the top and left side of the transduction path diagram are boxes, each containing a label indicating one of the seven forms of energy. These fourteen boxes represent the input measurand of a solid state sensor. Since every transduction path starts with an input measurand, these boxes also represent the fourteen possible points of origin of a transduction path. To remind the user of this fact, adjacent to these boxes are long, narrow, blocked-in areas labelled "INPUT". This particular portion of the transduction path diagram is illustrated in Figure 5.3.

2. Transduction Path Section

The body of the transduction path diagram is a 7 X 7 matrix which is used to illustrate the transduction and modification steps utilized in a solid state sensor. A transduction path begins with an input measurand and consists of a sequence of one or more transduction or modification steps. Each of these steps has an associated input and output measurand. The labels on the rows and columns of this portion of the diagram serve to identify the energy form of these measurands. A few observations are necessary to determine whether these labels should be read to indicate input or output and are described below.

Transduction and modification steps are indicated by lines which lie within a single row or column. A line lies within the row or column that has the same energy form as its input measurand. This same line terminates in the perpendicular row or column that has the same energy form as its output measurand.

This particular portion of the transduction path diagram is illustrated in Figure 5.4.

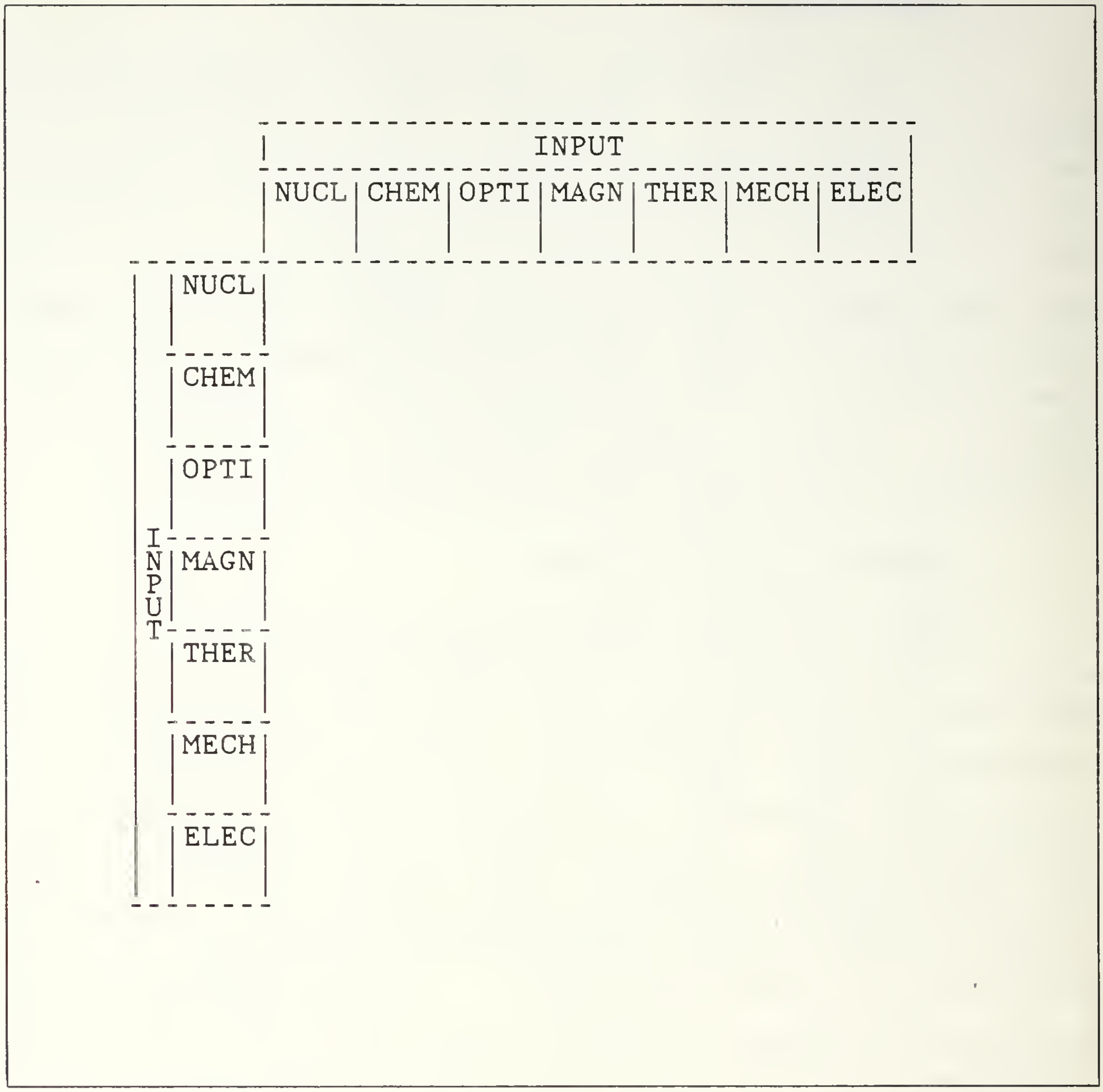


Figure 5.3 Input Measurand Section.

3. Output Section

On the bottom and right side of the transduction path diagram are thirteen boxes lying within the row and column labelled "ELEC". Adjacent to these thirteen boxes are long, narrow, blocked-in areas labelled "OUTPUT". These thirteen boxes also appear in the transduction path section

	NUCL	CHEM	OPTI	MAGN	THER	MECH	ELEC
NUCL							
CHEM							
OPTI							
MAGN							
THER							
MECH							
ELEC							

Figure 5.4 Transduction Path Section.

of the diagram, but have a special significance which must be mentioned here.

The box in the bottom right corner which lies both within the electrical row and the electrical column may be entered only through an electrical modification step. The other twelve boxes may be entered only through a transduction step which yields an electrical output. Since the end result of the transduction path of a solid state sensor is an electrical output signal, a transduction path could legitimately terminate in any of these thirteen boxes.

However, many transduction principles yield an electrical output that is not in a readily usable form. Typically, some signal processing or conditioning is necessary in order to obtain an electrical signal of significant strength and fidelity. Therefore, a transduction path that terminates in one of the twelve boxes mentioned above may be extended by one more step. This step would involve electronic signal processing and would result in a transduction path which ends in the bottom right box of the diagram. While any of the thirteen output boxes are legitimate termination points, the bottom right box is the preferred termination point. This particular portion of the transduction path diagram is illustrated in Figure 5.5.

C. A SAMPLE ANALYSIS

Earlier in this chapter, a pressure transducer was given as an example of a two step device. It utilized the principles of elastic deformation and piezoresistance to convert an input measurand, pressure, into an electrical output signal, resistance.

By referring to the tables of measurands in Chapter III, it can be seen that pressure is classified as a mechanical measurand. Therefore, the transduction path has a mechanical input measurand and will originate in an input block labelled "MECH", either at the top or left side of the diagram. Since the diagram is symmetric, these two blocks are equivalent and it is unimportant which of the two is actually chosen. However, to set a convention, assume that the block on the left side of the diagram is chosen to be the point of origin. Since the steps of the transduction path will be numbered as the example proceeds, a "0" is placed in the indicated block.

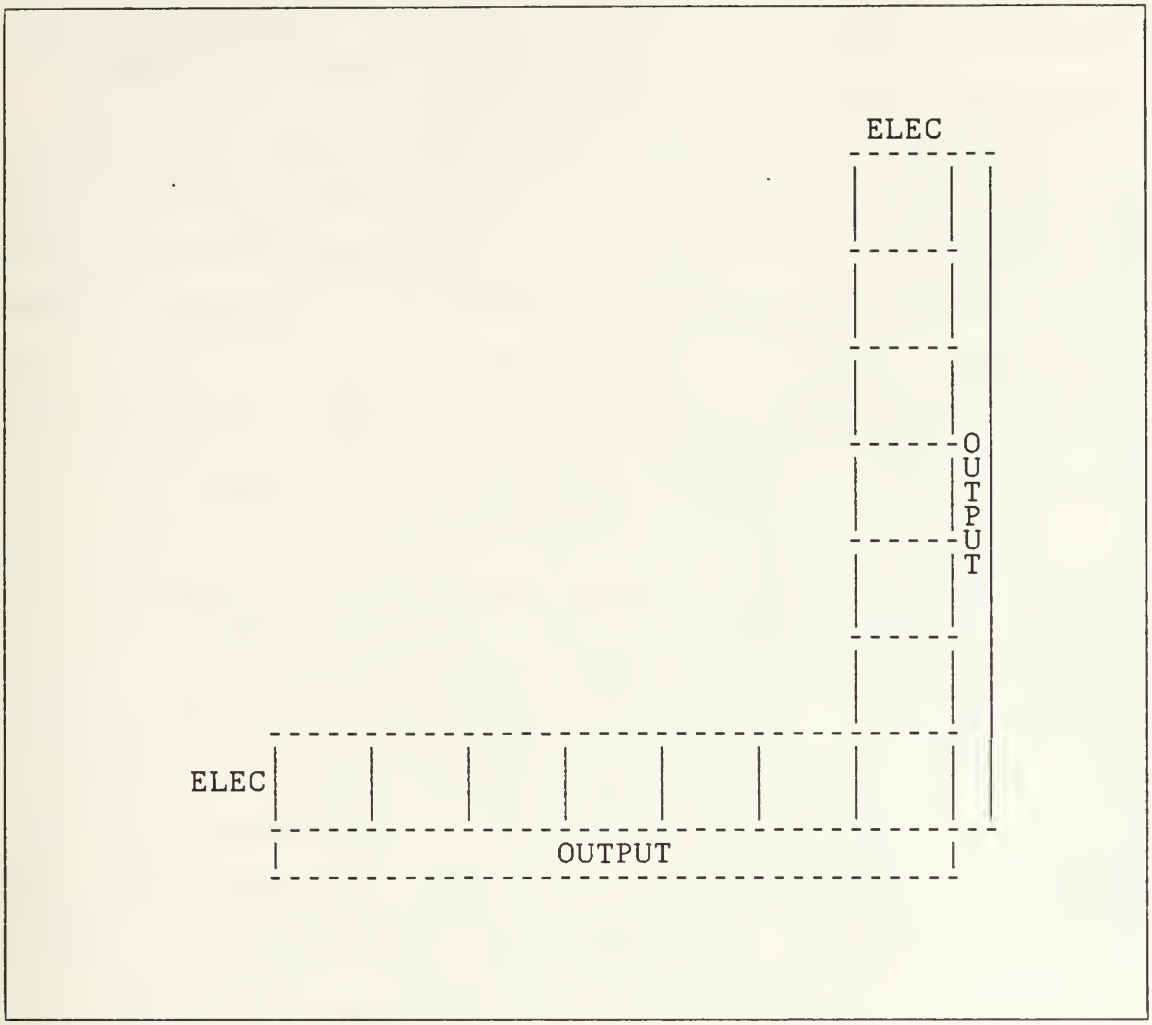


Figure 5.5 Output Signal Section.

The transduction path of a sensor consists of a sequence of transduction or modification principles. The example pressure transducer described above is a two step device which utilizes the principles of elastic deformation and piezoresistance. Elastic deformation modifies the mechanical input measurand, pressure, into a mechanical output measurand, strain. This strain is in turn applied as a mechanical input measurand to a piezoresistive device which transduces it to a change in electrical resistance.

The transduction path of this sensor would consist of a modification principle, elastic deformation, followed by a transduction principle, piezoresistance.

The point of origin for the transduction was selected previously to be on the left side of the diagram in the mechanical row. This initially specifies the rows to be input energy forms and the columns to be output energy forms.

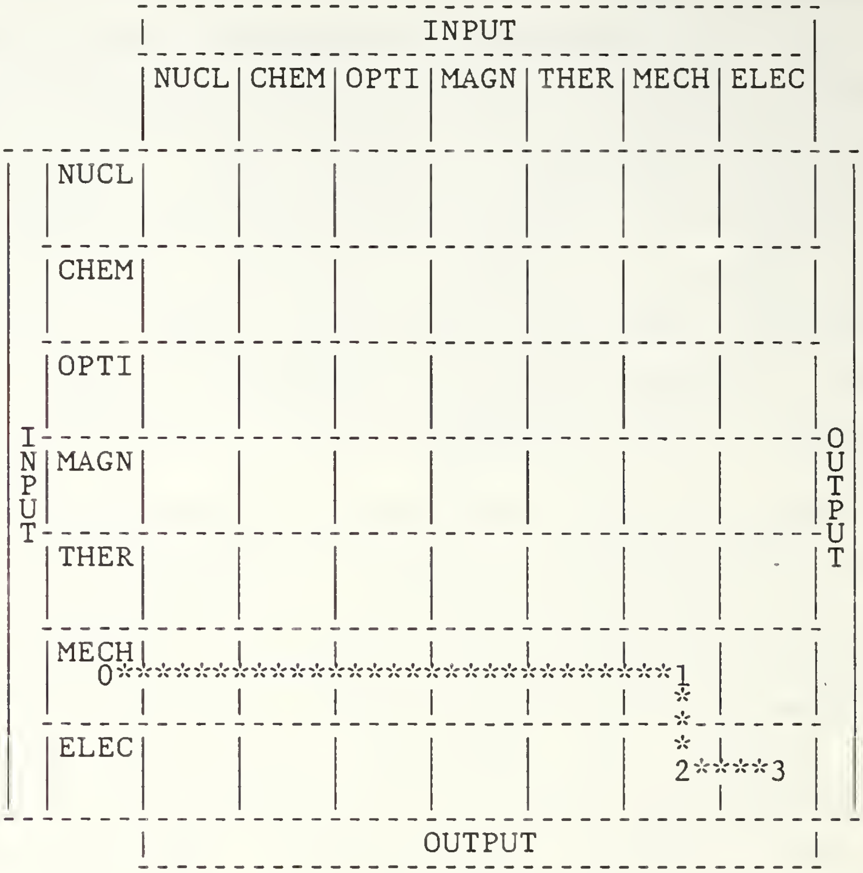
The first step of the transduction path is a principle known as elastic deformation. By referring to the tables in Chapter IV and the appropriate entry in Appendix N, it can be seen that elastic deformation is a mechanical modification principle. Therefore, a line is drawn from the point of origin along the row labelled "MECH", to be terminated in the block which lies in the output column labelled "MECH". In order to continue the numbering of the steps, a "1" is placed in this block. It is significant to note that this block lies on the diagonal of the transduction path diagram. It will be noted that all modification steps terminate in a block lying on the diagonal.

The second step of the transduction path is a principle known as piezoresistance. By referring to the tables in Chapter IV and the appropriate entry in Appendix O, it can be seen that piezoresistance is a mechanical to electrical transduction principle. The output energy form from the previous step of the transduction path becomes the input energy form for the current transduction step. This changes the input/output meaning of the rows and columns. The column labelled "MECH" is now the input energy form and the output energy form will be specified by the row designation. Therefore, a line is drawn from the ending point of the first step, along the column labelled "MECH", to be terminated in the block which lies in the output row labelled "ELEC". A "2" is placed in this block to continue the numbering scheme.

The final step necessary to complete the transduction path diagram is to ensure that a legitimate output signal is available. By definition, all solid state sensors must have an electrical output signal. This general requirement has been satisfied, for the path does indeed terminate in an electrical output row. However, the electrical signal being provided at the output is a very small change in resistance. This must be further processed to generate a signal that may be digitized and assimilated by a microprocessor or controller.

To accomplish this, an electrical modification step is appended to the transduction path. A Bridge Circuit would be a suitable electrical modifier to convert a small change in resistance to a usable output voltage. Therefore, a line is drawn from the termination of the previous step, along the electrical row, to terminate in the bottom right block of the transduction diagram. To finish the step numbering scheme, a "3" is entered in this block. This indicates that the transducer is actually a three step device when signal processing is included. Inclusion of the final electrical modification step is optional, but recommended in the majority of cases. Figure 5.6 shows the completed transduction path diagram with step numbers, measurands, and principles noted below the diagram.

The roles of the row and column labels alternate with each transduction or modification step. A transduction path with an even number of steps will end in a row if it begins in a row. Likewise, a transduction path with an even number of steps will end in a column if it begins in a column. In a similar manner, a three step transduction path which begins in an input row would terminate in an output column. Due to the symmetric nature of the diagram, similar results would be noted for any length odd or even transduction path.



INPUT	0	pressure
MODIFICATION	0-1	ELASTIC DEFORMATION
	1	strain
TRANSDUCTION	1-2	PIEZORESISTANCE
	2	resistance
MODIFICATION	2-3	BRIDGE CIRCUIT
OUTPUT	3	voltage

Piezoresistive Pressure Sensor

Figure 5.6 A Sample Three Step Transduction Path.

D. EXISTING TRANSDUCERS

The example presented above illustrates the general procedure to be followed when using the transduction path diagram as a method of sensor analysis. The transducer described may be regarded as being representative of a broad class of piezoresistive pressure transducers. However, the true test of the transduction path method lies in its ability to describe the widest range and variety of existing transducers.

In order to extensively test the transduction path method, information was collected on 108 different classes of sensors and transducers. This information was available in the form of articles from technical journals and specification sheets from manufacturers. The transduction path of each sensor was then determined and examined for compatibility with the transduction path diagram. The sensors examined were found to range from simple one step transduction paths to extremely complex seven step transduction paths. Each was found to be compatible with the transduction path method.

Due to the large number of sensors examined using this method, it is not practical to attempt to present all of the transduction paths here. Instead, one existing sensor has been chosen to represent each length of transduction path. In the sections below, a short description of each representative sensor is presented along with a completed transduction path diagram describing that sensor.

1. One Step

A representative example of a transducer with a one step transduction path is the Bridge Circuit, often referred to as a Wheatstone Bridge. It converts a small resistance change in one of its legs into a voltage which may be easily measured. This one step transduction path is illustrated in Figure 5.7.

This transducer, consisting of only a single step, illustrates the shortest transduction path possible. It is interesting to note that since a transduction path is required to terminate in the lower right block of the diagram, a single step transduction path must consist of an electrical modifier.

2. Two Step

A representative example of a transducer with a two step transduction path is the Solid State Thermistor. It converts the input measurand, temperature, into an electrical output signal which may be interfaced to digital circuitry. The two step transduction path of this device is illustrated in Figure 5.8.

The operation of the semiconductor thermistor is based on the thermoresistive effect. It is used primarily to measure temperature and has several advantages over the traditional generation of temperature sensors. These advantages include high temperature coefficient, small dimensions, and fast response. The high temperature coefficient eliminates many of the difficulties usually encountered when attempting to process the raw electrical output signal from the thermoresistance step. [Ref. 12]

This transduction path consists of two individual steps, a transduction followed by a modification. As noted earlier, the last step of a transduction path is required to be an electrical modifier. A Bridge Circuit is specified as the last step in this transduction path, but some other electrical modifier may serve just as well.

```
              ------------------------------------
              |              INPUT               |
              ------------------------------------
              |NUCL|CHEM|OPTI|MAGN|THER|MECH|ELEC|
              |    |    |    |    |    |    |    |
              |    |    |    |    |    |    |    |
   ----------------------------------------------------
   |  |NUCL|    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  ----------------------------------------------  |
   |  |CHEM|    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  ----------------------------------------------  |
   |  |OPTI|    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  I---------------------------------------------O |
   |  N|MAGN|    |    |    |    |    |    |    |    U |
   |  P|    |    |    |    |    |    |    |    |    T |
   |  U|    |    |    |    |    |    |    |    |    P |
   |  T---------------------------------------------U |
   |  |THER|    |    |    |    |    |    |    |    T |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  ----------------------------------------------  |
   |  |MECH|    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   |  ----------------------------------------------  |
   |  |ELEC|    |    |    |    |    |    |    |    |  |
   |  |   0********************************1   |  |  |
   |  |    |    |    |    |    |    |    |    |    |  |
   ----------------------------------------------------
              |              OUTPUT              |
              ------------------------------------

       INPUT              0      Resistance
       MODIFICATION       0-1    BRIDGE CIRCUIT
       OUTPUT             1      VOLTAGE
```

Bridge Circuit

Figure 5.7 One Step Transducer.

```
         ------------------------------------
         |              INPUT                |
         ------------------------------------
         |NUCL|CHEM|OPTI|MAGN|THER|MECH|ELEC|
         |    |    |    |    |    |    |    |
------------------------------------------------
  | |NUCL|    |    |    |    |    |    |    |  |
  | |    |    |    |    |    |    |    |    |  |
  | |    |    |    |    |    |    |    |    |  |
  | -----------------------------------------  |
  | |CHEM|    |    |    |    |    |    |    |  |
  | |    |    |    |    |    |    |    |    |  |
  | |    |    |    |    |    |    |    |    |  |
  | -----------------------------------------  |
  | |OPTI|    |    |    |    |    |    |    |  |
  | |    |    |    |    |    |    |    |    |  |
  | |    |    |    |    |    |    |    |    |  |
  I -----------------------------------------  O
  N |MAGN|    |    |    |    |    |    |    |  U
  P |    |    |    |    |    |    |    |    |  T
  U |    |    |    |    |    |    |    |    |  P
  T -----------------------------------------  U
  | |THER|    |    |    |    |    |    |    |  T
  | |  0**********************************1 |  |
  | |    |    |    |    |    |    |    |  * |  |
  | --------------------------------------*--  |
  | |MECH|    |    |    |    |    |    |  * |  |
  | |    |    |    |    |    |    |    |  * |  |
  | |    |    |    |    |    |    |    |  * |  |
  | --------------------------------------*--  |
  | |ELEC|    |    |    |    |    |    |  * |  |
  | |    |    |    |    |    |    |    |  2 |  |
  | |    |    |    |    |    |    |    |    |  |
------------------------------------------------
         |              OUTPUT               |
         ------------------------------------
```

INPUT	0	Temperature
TRANSDUCTION	0-1	THERMORESISTANCE
	1	Resistance
MODIFICATION	1-2	BRIDGE CIRCUIT
OUTPUT	2	Voltage

Solid State Thermistor

Figure 5.8 Two Step Transducer.

3. Three Step

A representative example of a transducer with a three step transduction path is the Integrated Silicon Microbeam PI-FET Accelerometer. It converts the input measurand, acceleration, into an electrical output signal. The three step transduction path of this device is illustrated in Figure 5.9.

The operation of the Integrated Silicon Microbeam PI-FET Accelerometer is based on the piezoelectric effect and the principle of elastic deformation. It is fabricated utilizing silicon planar technology, zinc-oxide sputtering, and anisotropic etching. A small cantilever beam is etched out of monolithic silicon and coated with a piezoelectric film. When the device undergoes acceleration, the cantilever beam flexes as does the piezoelectric coating. This creates a surface charge on the piezoelectric film. Due to careful isolation of the piezoelectric film from electrical leakage paths, a near-dc response is achieved up to 40 kHz. [Ref. 13]

This transduction path consists of three individual steps. The first is a modification, the second is a transduction, and the third is an electrical modifier. In this case, the last step is a PI-FET structure which converts charge to an amplified output voltage. The surface charge induced on the piezoelectric material is capacitively coupled to the gate of the p-channel, depletion mode FET with an amplified signal appearing at the drain [Ref. 13].

4. Four Step

A representative example of a transducer with a four step transduction path is the Wiegand Pulse Generator, often used in automotive engine control applications. It converts the input measurand, vane position, into an electrical

```
              ------------------------------------
              |              INPUT               |
              ------------------------------------
              |NUCL|CHEM|OPTI|MAGN|THER|MECH|ELEC|
              |    |    |    |    |    |    |    |
      -----------------------------------------------
      |  |NUCL|    |    |    |    |    |    |    |  |
      |  |    |    |    |    |    |    |    |    |  |
      |  -----------------------------------------  |
      |  |CHEM|    |    |    |    |    |    |    |  |
      |  |    |    |    |    |    |    |    |    |  |
      |  -----------------------------------------  |
      |  |OPTI|    |    |    |    |    |    |    |  |
      |  |    |    |    |    |    |    |    |    |  |
      | I-----------------------------------------O |
      | N|MAGN|    |    |    |    |    |    |    |U |
      | P|    |    |    |    |    |    |    |    |T |
      | U|    |    |    |    |    |    |    |    |P |
      | T-----------------------------------------U |
      |  |THER|    |    |    |    |    |    |    |T |
      |  |    |    |    |    |    |    |    |    |  |
      |  -----------------------------------------  |
      |  |MECH|    |    |    |    |    |    |    |  |
      |  |  0*****************************1 |    |  |
      |  |    |    |    |    |    |    |  * |    |  |
      |  ---------------------------------*-------  |
      |  |ELEC|    |    |    |    |    |  * |    |  |
      |  |    |    |    |    |    |    |  2****3 |  |
      |  |    |    |    |    |    |    |    |    |  |
      -----------------------------------------------
              |             OUTPUT               |
              ------------------------------------
```

INPUT	0	Acceleration
MODIFICATION	0-1	ELASTIC DEFORMATION
	1	Strain
TRANSDUCTION	1-2	PIEZOELECTRIC
	2	Charge
MODIFICATION	2-3	CAPACITIVE PI-FET
OUTPUT	3	Voltage

Integrated Silicon Microbeam PI-FET Accelerometer

Figure 5.9 Three Step Transducer.

output signal. The four step transduction path of this device is illustrated in Figure 5.10.

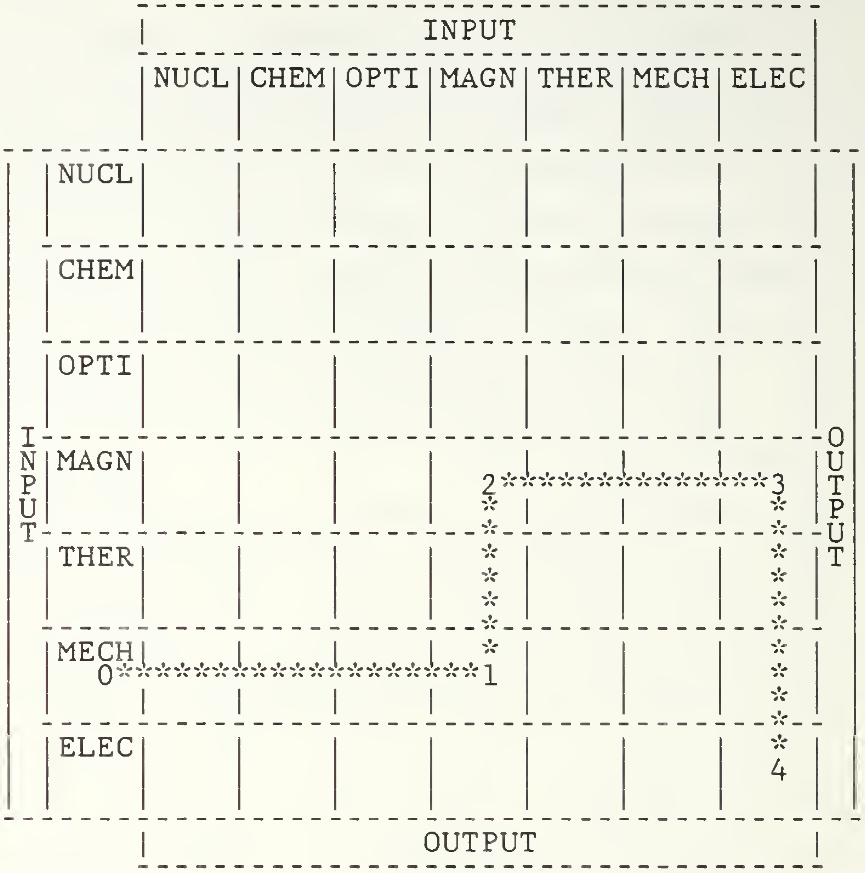
The Wiegand Effect is a magnetic phenomenon which occurs in a specially work-hardened small diameter ferro-magnetic wire. When a properly shaped magnetic field is applied, the Wiegand Wire acts as a bi-stable magnetic device. It changes from one magnetic state to the other by means of a rapid internal flux change. This flux change may be used to induce a quite substantial voltage in a nearby sensing coil. A particular feature worth noting is that the Wiegand Wire does not require an electrical input for its operation. [Ref. 14]

The Wiegand Pulse Generator operates upon the Wiegand Effect and the principles of variable reluctance and Faraday induction. The position of a soft-magnetic rotating vane influences the magnetic field of a permanent magnet through the principle of variable reluctance. The magnetic field is converted to a rapid flux change by the Wiegand Wire. This flux change is then used to induce a voltage in a sensing coil through the process of Faraday induction.

The transduction path of this device consists of four individual steps. These are, in order, a transduction, a modification, a transduction, and an electrical modifier. In this case, the last step is not specified beyond the general term, signal processing. The output of the sensing coil has been observed to range anywhere between one-half and ten volts [Ref. 14]. Therefore, the signal processing may consist of amplification, analog to digital conversion, or some other suitable electrical modifier.

5. Five Step

A representative example of a transducer with a five step transduction path is the Fiber Optic Magnetic Field Sensor. It converts the input measurand, magnetic field,



INPUT	0	Position
TRANSDUCTION	0-1	VARIABLE RELUCTANCE
	1	Magnetic Field
MODIFICATION	1-2	WIEGAND EFFECT
	2	Flux Change
TRANSDUCTION	2-3	FARADAY INDUCTION
	3	Emf
MODIFICATION	3-4	SIGNAL PROCESSING
OUTPUT	4	Voltage

Wiegand Pulse Generator

Figure 5.10 Four Step Transducer.

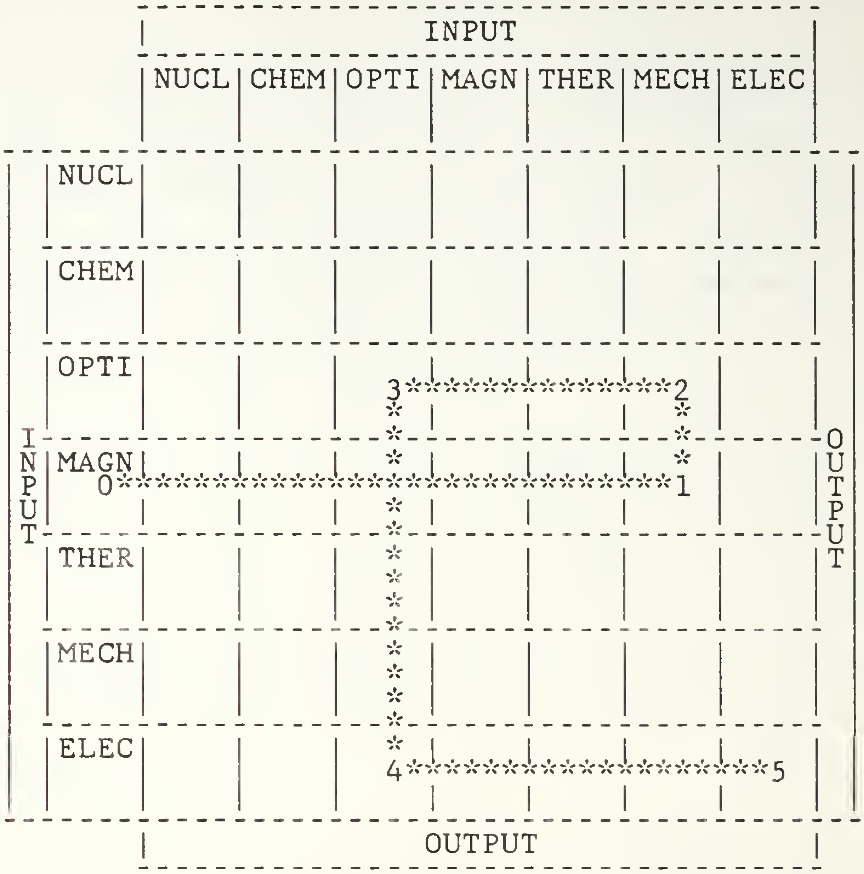
into an electrical output signal. The five step transduction path of this device is illustrated in Figure 5.11.

The operation of the Fiber Optic Magnetic Field Sensor is based on the elasto-optic effect, the phase interferometer, and the principles of magnetostriction and photoconductance. The main principle by which this sensor operates is magnetostriction. An optical fiber is jacketed by a magnetostrictive material which produces a longitudinal strain when exposed to a magnetic field. This strain induces a refractive index change in the optical fiber due to the elasto-optic effect. The refractive index change affects the manner in which light is propagated through the fiber and may be detected through the use of a phase interferometer. The phase interferometer has an optical power output which is allowed to fall upon a photoconductive device. This photoconductive device converts the incident optical power to a change in electrical resistance. [Ref. 15]

This transduction path consists of five individual transduction and modification principles, the last of which must be an electrical modifier. In this case, the last step is not specified beyond the general term, signal processing. The signal processing may consist of a Bridge Circuit or some other suitable electrical modifier capable of converting a change in resistance to voltage.

6. Six Step

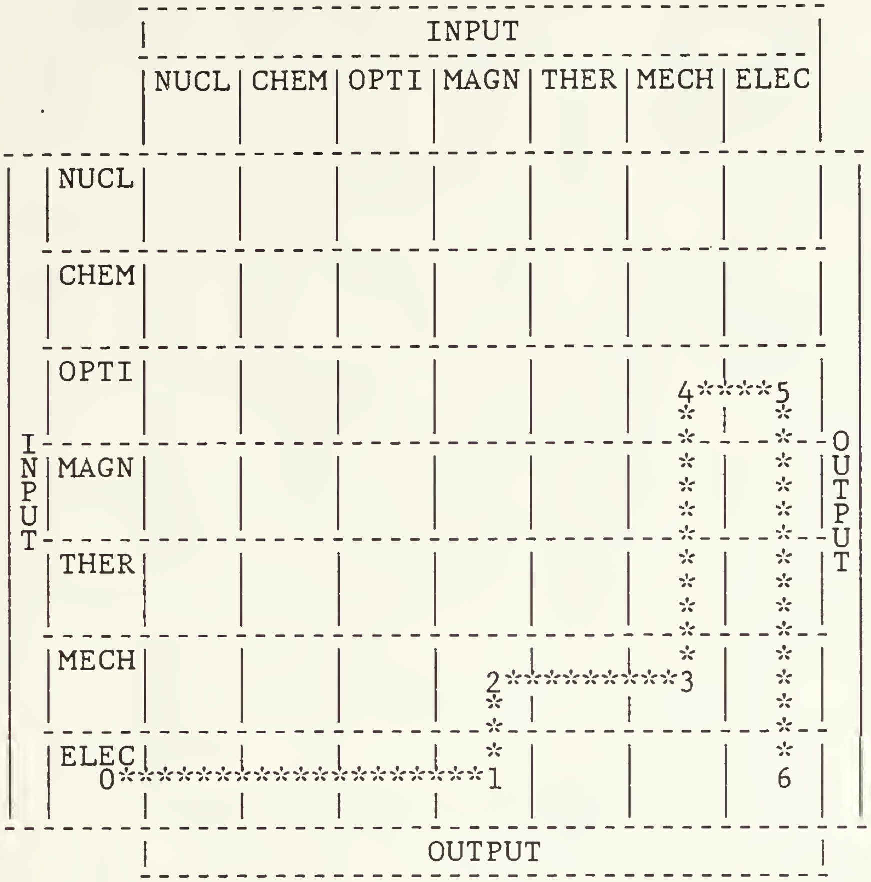
A representative example of a transducer with a six step transduction path is the Laser Diode Current Sensor. It converts the input measurand, current, into an electrical output signal. An important advantage of this sensor is that the current sensing is accomplished in a non-contacting manner. The six step transduction path of this device is illustrated in Figure 5.12.



INPUT	0	Magnetic Field
TRANSDUCTION	0-1	MAGNETOSTRICTION
	1	Strain
TRANSDUCTION	1-2	ELASTO-OPTIC EFFECT
	2	Refractive Index
MODIFICATION	2-3	PHASE INTERFEROMETER
	3	Optical Power
TRANSDUCTION	3-4	PHOTOCONDUCTIVE
	4	Resistance
MODIFICATION	4-5	SIGNAL PROCESSING
OUTPUT	5	Voltage

Fiber Optic Magnetic Field Sensor

Figure 5.11 Five Step Transducer.



INPUT	0	Current
TRANSDUCTION	0-1	FARADAY INDUCTION
	1	Magnetic Field
TRANSDUCTION	1-2	MAGNETOSTRICTION
	2	Strain
MODIFICATION	2-3	ELASTIC DEFORMATION
	3	Position
TRANSDUCTION	3-4	LASER EXTERNAL MIRROR
	4	Optical Power
TRANSDUCTION	4-5	PHOTOCONDUCTIVE
	5	Resistance
MODIFICATION	5-6	SIGNAL PROCESSING
OUTPUT	6	Voltage

Laser Diode Current Sensor

Figure 5.12 Six Step Transducer.

A laser diode configured with an external reflector will undergo large changes in output intensity as the external reflector is moved a very small distance. This movement of the external reflector changes the phase of the light which is reflected back into the laser cavity. When the phase of the reflected light is such that in-phase feedback occurs, the output intensity of the laser diode is increased. When the phase of the reflected light is such that out-of-phase feedback occurs, the output intensity of the laser diode is decreased. Since the wavelength of light is very short, a very small displacement of the external reflector may be detected in this manner. [Ref. 15]

The Laser Diode Current Sensor operates upon the principles of magnetostriction, Faraday induction, photoconductance, elastic deformation, and the laser external mirror. Current passing through a conductor induces a magnetic field about that conductor through Faraday induction. A coil of the conductor is wrapped around a length of magnetostrictive tubing upon the end of which is mounted a laser external mirror. The magnetic field caused by the current in the conductor induces a strain in the magnetostrictive material. The strain in the magnetostrictive material causes the laser external mirror mounted thereupon to change its relative position. As the position changes, the laser output intensity likewise changes due to the feedback of the laser external mirror. This optical output power is converted to resistance through the action of a photoconductive device.

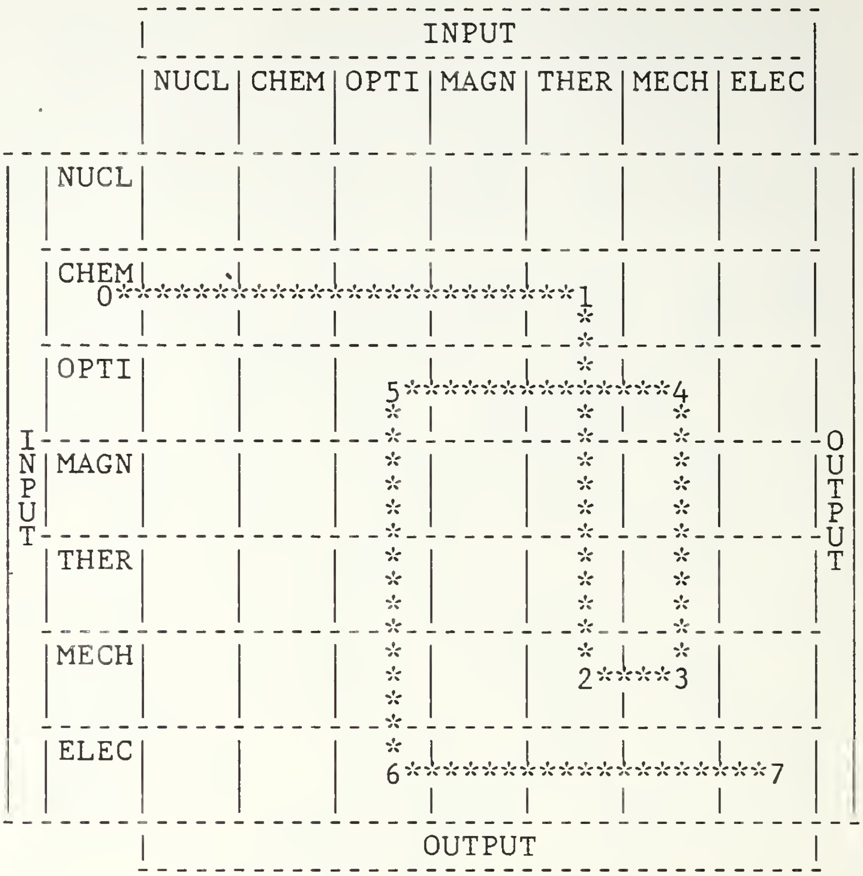
The transduction path of this device is rather long and complicated. However, as in all cases, the final step must be an electrical modifier. In this case, the last step is not specified beyond the general term, signal processing. The signal processing may consist of a Bridge Circuit or some other suitable electrical modifier capable of converting a change in resistance to voltage.

7. Seven Step

A representative example of a transducer with a seven step transduction path is the Fiber Optic Spectrophone. It converts the input measurand, chemical composition, into an electrical output signal. The seven step transduction path of this device is illustrated in Figure 5.13.

The Fiber Optic Spectrophone operates in much the same manner as an optical fiber acoustic sensor utilizing interferometric techniques. An optical absorption cell contains the trace chemical compound to be detected. The cell is irradiated by a laser beam of an appropriate wavelength. This raises the temperature of the trace gas through the process of photoabsorption. As the gas heats, the pressure within the cell increases due to thermal expansion. This pressure increase causes the cell to expand, inducing a strain upon an optical fiber wrapped around the cell. The elasto-optic effect converts this strain to a refractive index change which is in turn detected by a phase interferometer. The phase interferometer has an optical power output which is allowed to fall upon a photoconductive device. The photoconductive device then converts the incident optical power to electrical resistance. [Ref. 15]

This transduction path represents a very complex device which utilizes a long sequence of transduction and modification principles. However, it is different only in degree from a simple one step device. The same methodology applies to all sensors and transduction paths, regardless of length. They all begin with an input measurand and terminate with an electrical modification step.



INPUT	0	Chemical Composition
TRANSDUCTION	0-1	PHOTOABSORPTION
	1	Temperature
TRANSDUCTION	1-2	THERMAL EXPANSION
	2	Pressure
MODIFICATION	2-3	ELASTIC DEFORMATION
	3	Strain
TRANSDUCTION	3-4	ELASTO-OPTIC EFFECT
	4	Refractive Index
MODIFICATION	4-5	PHASE INTERFEROMETER
	5	Optical Power
TRANSDUCTION	5-6	PHOTOCONDUCTIVE
	6	Resistance
MODIFICATION	6-7	SIGNAL PROCESSING
OUTPUT	7	Voltage

Fiber Optic Spectrophone

Figure 5.13 Seven Step Transducer.

E. A SAMPLE INVESTIGATION

In the previous section, the transduction path method was shown to be useful as a sensor description and analysis technique. Existing sensors of various transduction path lengths were presented and analyzed through use of the transduction path method. However, the method is also useful as a means of investigating sensor configurations. For any given class of sensor, the method is capable of systematically generating all possible sensor configurations utilizing the known transduction and modification principles. The actual techniques employed are similar to those presented in previous sections and are not presented here. Appendix P may be consulted for further details.

The sensor configurations thus generated may be broken down into two groups. The first group consists of those transduction paths which have actually been implemented as actual sensor designs. The second group consists of those transduction paths which have not been implemented as actual sensor designs. The latter group would require closer examination to determine whether or not they might be feasible as potential sensor configurations.

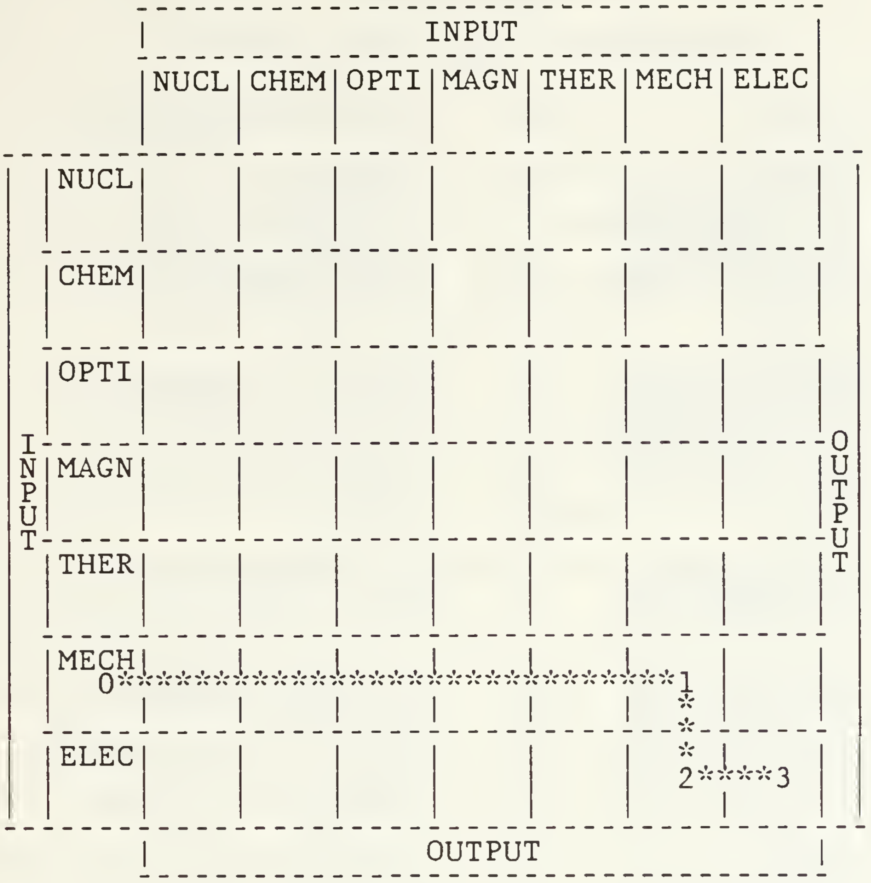
In this section, an investigation is made of all possible three step pressure sensor configurations. The techniques described in Appendix P are utilized to generate all possible transduction paths of the requisite length which lead from the input measurand, pressure, to an electrical output signal. The first and second step may consist of either transduction or modification principles, while the last step is an electrical modifier.

An examination of the tables contained in Chapter IV reveals that only two principles are listed which have pressure as an input measurand and also have a non-electrical output measurand. The two principles thus identified are elastic deformation and triboluminescence. These principles convert the input measurand, pressure, into mechanical and optical forms of energy, respectively. These principles would be candidates for the first step of the transduction path. The second step would consist of either a transduction or a modification principle drawn from Tables XI and XII. Examination of these tables reveals that 18 transduction or modification principles exist which satisfy the necessary conditions. The third step would, of course, be an electrical modifier drawn from Table XII. In the subsequent investigation, this step will simply be identified as "Signal Processing".

Based upon the above observations, three step pressure sensors may be divided into two general categories. The categories are based upon the energy form of the first intermediate measurand of the transduction path. Since the two candidates for the first step are elastic deformation and triboluminescence, the two categories are mechanical and optical. In the following sections, the sensor configurations within each category are discussed. Furthermore, each configuration is examined to determine if it represents an actual sensor design or a potential sensor design.

1. Mechanical Three Step Pressure Sensors

A generalized transduction path diagram has been prepared for each of the two categories identified above. Associated with each diagram is a listing of those combinations of principles which have been found to satisfy that particular transduction path. In the case of three step pressure sensors which utilize elastic deformation as their first step, the diagram would appear as illustrated in Figure 5.14. This generalized transduction path diagram is representative of the 13 possible sensor configurations identified in Tables XVIII and XIX.



INPUT	0
PRINCIPLE	0-1
INTERMEDIATE	1
PRINCIPLE	1-2
INTERMEDIATE	2
MODIFICATION	2-3
OUTPUT	3

Figure 5.14 Mechanical Three Step Pressure Sensor.

TABLE XVIII

Mechanical Three Step Paths I

	Step	No.	Measurand/Principle
Path #1	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Deflection
	TRANSDUCTION	1-2	VARIABLE DIELECTRIC
	INTERMEDIATE	2	Capacitance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #2	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Displacement
	TRANSDUCTION	1-2	VARIABLE RELUCTANCE
	INTERMEDIATE	2	Inductance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #3	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Microbends
	TRANSDUCTION	1-2	NONE, PATH INCOMPLETE
Path #4	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Position
	TRANSDUCTION	1-2	CONDUCTIVE ELASTOMER
	INTERMEDIATE	2	Resistance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #5	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Position
	TRANSDUCTION	1-2	MECHANICAL SWITCH
	INTERMEDIATE	2	Resistance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #6	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Position
	TRANSDUCTION	1-2	POTENTIOMETRIC
	INTERMEDIATE	2	Resistance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #7	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Position
	TRANSDUCTION	1-2	VARIABLE RELUCTANCE
	INTERMEDIATE	2	Inductance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage

See Figure 5.14 for appropriate transduction path diagram.

The configurations listed in Tables XVIII and XIX have been labelled as paths 1 through 13. It is now necessary to examine each of the proposed sensor configurations to determine whether or not it represents an actual sensor design. If not, a closer look is taken to determine if it is a feasible, but untried, design.

Transduction path #1 represents a sensor configuration which has been implemented in actual sensor designs. This particular configuration is commonly referred to as a Capacitance Manometer and has been described in [Ref. 16]. Briefly, the device operates by subjecting a sensing diaphragm to the pressure which is to be measured. The diaphragm is a common element in a double-sided capacitor plate arrangement. When the diaphragm deflects in response to the applied pressure, the geometry of the capacitor arrangement changes and a differential capacitance is generated. In general, a change in capacitance may be obtained in two ways. In this example, the spacing of the metallic elements is changed. This alters the thickness of the dielectric while keeping the dielectric constant fixed. A second way to generate a capacitance change is to alter the dielectric constant while keeping the plate spacing fixed as may be seen in path #10. As a final step, the capacitance change is detected by electronic circuitry and a suitable output signal generated. [Ref. 17]

Path #2 is a transduction path configuration which has been implemented in present day sensor designs as an LVDT Pressure Transducer. The device operates by subjecting a sensing diaphragm to the pressure which is to be measured. The diaphragm is mechanically connected to the core element of a linear variable differential transformer (LVDT). When the diaphragm deflects in response to the applied pressure, the core of the LVDT is displaced. This changes the induction ratio of the differential transformer because the

TABLE XIX

Mechanical Three Step Paths II

	Step	No.	Measurand/Principle
Path #8	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Proximity
	TRANSDUCTION	1-2	PROXIMITY EFFECT
	INTERMEDIATE	2	Resistance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #9	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Strain
	TRANSDUCTION	1-2	PIEZOELECTRIC
	INTERMEDIATE	2	Charge or Emf
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #10	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Strain
	TRANSDUCTION	1-2	PIEZO-OPTICAL
	INTERMEDIATE	2	Dielectric Constant
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #11	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Strain
	TRANSDUCTION	1-2	PIEZORESISTANCE
	INTERMEDIATE	2	Resistance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #12	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Strain
	TRANSDUCTION	1-2	PN PIEZOJUNCTION
	INTERMEDIATE	2	Current
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
Path #13	INPUT	0	Pressure
	MODIFICATION	0-1	ELASTIC DEFORMATION
	INTERMEDIATE	1	Strain
	TRANSDUCTION	1-2	THERMOELASTIC EFFECT
	INTERMEDIATE	2	Emf
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage

See Figure 5.14 for appropriate transduction path diagram.

reluctance of the core is being altered. The induction ratio is manifested as a differential voltage between the windings of the LVDT. It is this voltage which forms the useful electrical output of the transducer. [Ref. 18]

Path #3 is not a complete transduction path. As such, it is not a useful three step sensor configuration and may be discarded. It is important to note, however, that the transduction path may be completed if more steps are permitted. Such a device would be an Optical Fiber Microbend Pressure Transducer and is described in [Ref. 15].

Transduction path #4 is a sensor configuration which has been implemented as an actual sensor design. Conductive elastomers [Ref. 19] have been recently developed which exhibit very low hysteresis and small compression set. They are being used primarily in tactile sensors with a useful range from 1 to 40 psi. When a force or pressure is applied to the sensor pad, the compliance affords deflections which conform to the pressure pattern. The deflections increase the internal conductivity of the elastomer which may be detected through appropriate interface circuitry. [Ref. 19]

Path #5 represents a transduction path which has been implemented in present day sensor designs. The configuration has been described in [Ref. 20] and is commonly referred to as a Pressure Switch. The device operates by exposing an elastic diaphragm to the pressure which is being sensed. When the pressure exceeds a predetermined threshold, the diaphragm deforms sufficiently to close, or open, a mechanical switch. The action of the mechanical switch results in either a short or an open circuit which is then detected by appropriate signal processing.

Transduction path #6 represents a sensor configuration which has been implemented as an actual sensor design. The configuration is a Potentiometric Pressure

Transducer which has been described in [Ref. 21]. The device is constructed in a manner similar to the Pressure Switch described above. An elastic diaphragm is exposed to the pressure to be measured. Attached to the diaphragm is a contact which is caused to move across a precision potentiometer as the pressure changes. The output of the potentiometer is read as a resistance, or a resistance ratio, and may be easily converted to an equivalent pressure reading.

Path #7 represents a sensor configuration known as a Variable Reluctance Pressure Transducer. It has been implemented in actual sensor designs and is described in [Ref. 22]. The operation is virtually identical to the LVDT Pressure Transducer described above. The primary difference is in the mechanical design of the elastic diaphragm. In this particular configuration, the diaphragm is constructed of a magnetically permeable material. It is situated between two symmetric transformer assemblies and completes a magnetic circuit with each E-core. As pressure is applied, the diaphragm deflects toward one transformer assembly and away from the other. This increases the gap in the magnetic flux path of one core and decreases it in the other. As the gaps become unequal, the induction ratio between the two transformer assemblies changes. This ratio is conveniently measured in an AC bridge circuit which provides an output voltage proportional to the applied pressure. [Ref. 22]

Path #8 represents a sensor configuration which, to the knowledge of the author, has not been implemented as an actual sensor design. Such a device, if implemented, would utilize the principle of elastic deformation to convert pressure to a relative position or displacement. An elastic diaphragm exposed to the pressure to be measured would undergo a displacement proportional to the applied pressure. When a wire is carrying an alternating current, the current has a tendency to crowd toward one side of a conductor owing to the proximity another current-carrying conductor. This increases the resistance and is known as the proximity effect [Ref. 11]. Through a suitable mechanical arrangement, the displacement of the diaphragm could be used to change the separation between two such conductors. If desired, the device could even be configured as a differential device using three conductors. Similar to the Capacitance Manometer described above, the device would have a current carrying conductor on the elastic diaphragm. Conductors carrying electrical current would be located on either side of the diaphragm. As the diaphragm is displaced, the spacing between conductors would be altered and a differential resistance would be measured. Utilizing a suitable bridge circuit, the differential resistance could be converted into a useful electrical signal.

Transduction path #9 is representative of a general class of existing piezoelectric pressure transducers. A related device, the Integrated Silicon Microbeam PI-FET Accelerometer [Ref. 13], has already been described in this chapter. A pressure sensing device would differ from an accelerometer only in the first step of the transduction path. In a pressure sensor, the silicon microbeam would be replaced by an elastic diaphragm. This would change the manner in which force is converted to strain. The rest of the transduction path would, however, remain the same.

Path # 10 is a sensor configuration which has been implemented in actual sensor designs. The configuration is known as a Capacitance Manometer and is closely related to the device described by path #1. This particular device, however, relies upon a change in dielectric constant to cause a capacitance change. Otherwise, the device is virtually identical to path #1.

Path #11 describes the operation of an existing sensor configuration known as a Thin-Diaphragm Piezoresistive Pressure Sensor [Ref. 23]. The operation of the device is based upon the exposure of a thin, elastic diaphragm to the pressure which is to be measured. Diffused upon the diaphragm are several piezoresistors which flex along with the diaphragm as it flexes under pressure. The resulting change in resistance is easily detected through use of a suitable electrical bridge circuit. An advantage of this type of device is that it operates at fairly low stress levels. However, the device sensitivity is quite dependent upon diaphragm thickness. [Ref. 24]

Path #12 is a sensor configuration which has been implemented in present day sensor designs. It has been described in [Ref. 25] and is commonly referred to as a Piezojunction Pressure Transducer. Pressure is converted to mechanical strain through use of an appropriate elastic structure such as a cantilever, diaphragm, or beam. Fabricated upon the structure is a PN piezojunction which changes its electrical characteristics as it undergoes strain. In particular, the electrical current through the piezojunction varies as a function of strain. This current is then amplified and converted to voltage through appropriate signal processing.

Transduction path #13 is the last of the mechanical pressure sensor configurations to be explored. This configuration, to the best knowledge of the author, has not been implemented as an actual sensor design. The thermoelastic effect is the production of an electrical potential between two points in a stressed metal which are maintained at a constant temperature difference [Ref. 11]. The actual voltage generated is a function of the stress intensity and the temperature difference. Such a device, if implemented, would utilize the principle of elastic deformation to convert pressure to a mechanical strain in metal. This strain would then be converted to an electrical potential through use of the thermoelastic effect. Since maintenance of a constant temperature difference is necessary, some temperature control circuitry would be necessary.

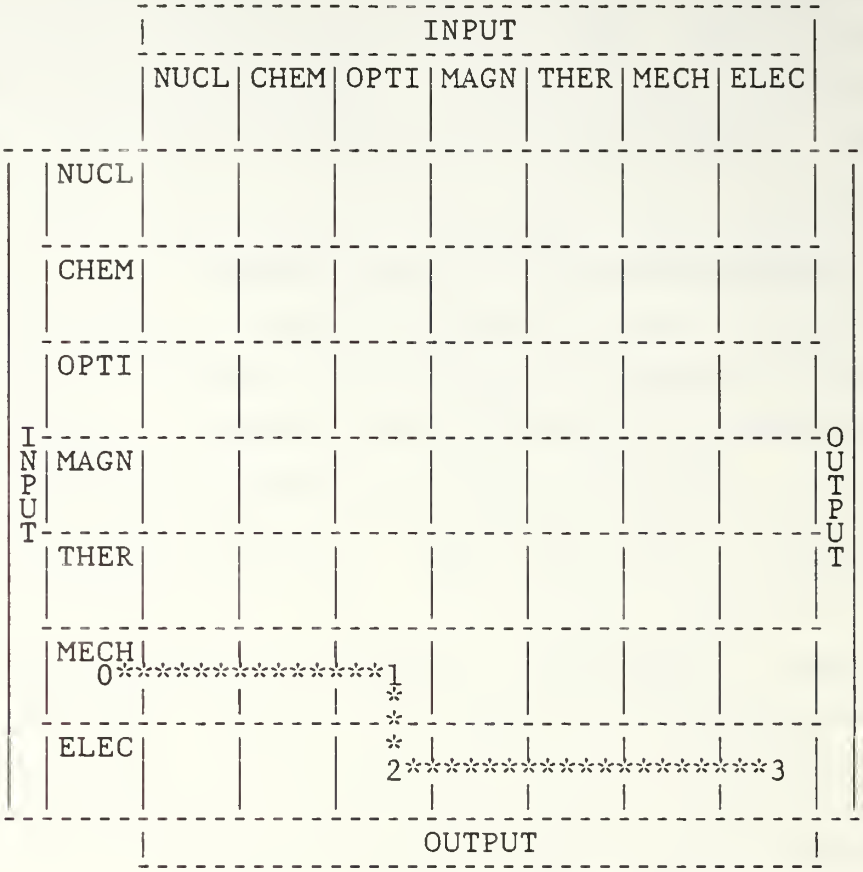
2. Optical Three Step Pressure Sensors

A generalized transduction path diagram for optical three step pressure sensors is illustrated in Figure 5.15. This generalized transduction path diagram is representative of the six possible sensor configurations identified in Table XX. Each of these configurations utilizes triboluminescence as the first step of the transduction path.

The configurations listed in Table XX have been labelled as paths 14 through 19. To the knowledge of the author, these six configurations have not been implemented as actual sensor designs. It is now necessary to examine each of the proposed sensor configurations to determine if any may represent a feasible sensor design.

Triboluminescence is an effect which causes a material to emit a glow when scratched, struck, or broken. Only a few materials such as sugar, mica, uranium salts, and ice exhibit this effect. [Ref. 11]

The six transduction paths identified in Table XX all utilize triboluminescence as their first step and some photoelectric effect as their second step. In order to implement any of the six configurations, a suitable mechanical arrangement would be necessary to inflict the necessary damage to the triboluminescent material as a function of pressure. Since damage to the material is necessary in order to cause the effect, such a sensor would probably have to be expendable after one use. It would



INPUT	0
PRINCIPLE	0-1
INTERMEDIATE	1
PRINCIPLE	1-2
INTERMEDIATE	2
MODIFICATION	2-3
OUTPUT	3

Figure 5.15 Optical Three Step Pressure Sensor.

TABLE XX

Optical Three Step Paths

	Step	No.	Measurand/Principle
	INPUT	0	Pressure
	TRANSDUCTION	0-1	TRIBOLUMINESCENCE
	INTERMEDIATE	1	Optical Power
Path #14	TRANSDUCTION	1-2	APD
	INTERMEDIATE	2	Current
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
	INPUT	0	Pressure
	TRANSDUCTION	0-1	TRIBOLUMINESCENCE
	INTERMEDIATE	1	Optical Power
Path #15	TRANSDUCTION	1-2	PHOTOCONDUCTIVE
	INTERMEDIATE	2	Resistance
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
	INPUT	0	Pressure
	TRANSDUCTION	0-1	TRIBOLUMINESCENCE
	INTERMEDIATE	1	Optical Power
Path #16	TRANSDUCTION	1-2	PHOTOEMISSIVE
	INTERMEDIATE	2	Charge Carrier
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
	INPUT	0	Pressure
	TRANSDUCTION	0-1	TRIBOLUMINESCENCE
	INTERMEDIATE	1	Optical Power
Path #17	TRANSDUCTION	1-2	PHOTOVOLTAIC
	INTERMEDIATE	2	Emf
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
	INPUT	0	Pressure
	TRANSDUCTION	0-1	TRIBOLUMINESCENCE
	INTERMEDIATE	1	Optical Power
Path #18	TRANSDUCTION	1-2	PHOTOVOLTAIC
	INTERMEDIATE	2	Electric Field
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage
	INPUT	0	Pressure
	TRANSDUCTION	0-1	TRIBOLUMINESCENCE
	INTERMEDIATE	1	Optical Power
Path #19	TRANSDUCTION	1-2	PIN PHOTOCURRENT
	INTERMEDIATE	2	Current
	MODIFICATION	2-3	SIGNAL PROCESSING
	OUTPUT	3	Voltage

See Figure 5.15 for appropriate transduction path diagram.

likely find application in the detection of detonation pressure waves and other impulse-like phenomena.

The second step varies among the six configurations being considered. Path #14 proposes using an avalanche photodiode (APD) as a means of detecting the light generated by the triboluminescent material. In a like manner, paths 15 through 19 utilize photoconductance, the photoemissive effect, the photovoltaic effect, and a PIN photodiode to convert light to electricity. The APD appears to be the most promising device for the second step due to its inherent gain since the light emission from the triboluminescent material is likely to be small. The PIN photodiode would probably be the second choice, followed thereafter by the other photoelectric effects.

F. CONCLUSIONS

The transduction path method has been shown to be useful for sensor description and analysis. It is capable of describing the operation of any single or multistep transducer. The method is also useful for sensor configuration investigation. It is capable of systematically generating all possible sensor configurations of a given class which utilize the known transduction and modification principles.

An investigation was carried out of all possible three step pressure sensor configurations. The investigation resulted in the generation of 19 possible transduction paths. One of these paths was incomplete. Ten of the paths represented sensor configurations which presently exist. However, eight paths were found which do not correspond to any of the sensor types examined in the course of this project.

To the best knowledge of the author, these eight configurations have never been implemented as actual sensor designs. While none of the new configurations appear to be promising as replacements for existing transducers, they may prove to be feasible within a narrow range of applications. However, further research and appropriate paper designs would be necessary.

VI. SUMMARY AND CONCLUSIONS

A. SUMMARY

The purpose of a solid state sensor is to convert an input measurand to an electrical output signal. The input measurand is manifested as a signal belonging to one of seven different forms of energy. These forms include mechanical, thermal, electrical, magnetic, optical, chemical, and nuclear energy. Complete listings of physical quantities associated with each form of energy have been attached as Appendices A through G.

When this signal is other than electrical in nature, it must undergo the process of transduction before it can be processed by electronic devices. This process of transduction may be described through what is now referred to as the "transduction path" method. The method defines a transduction path as a sequence of individual transduction or modification principles which lead from an input measurand to an electrical output signal. Transduction is the process by which one form of energy is converted into another form of energy and modification is the process by which one form of energy is changed to a like form of energy.

The transduction path method represents a means of describing the operation of a solid state sensor. However, it requires knowledge of transduction and modification principles drawn from all fields of science. It is for this reason that the known transduction and modification principles have been tabulated alphabetically in Appendix H and by energy form in Appendices I through O.

One way to represent these transduction and modification principles is in matrix form. A symmetric 7 X 7 matrix with rows and columns corresponding to the seven forms of energy is sufficient to illustrate all possible transduction and modification elements. The number of principles belonging to each family, based on input-output energy forms, have been annotated in Figure 6.1. The number in each block represents the number of known principles drawn from all fields of science which make that particular energy transduction or modification possible.

In order to extensively test the transduction path method, information was collected on 108 different classes of sensors and transducers. This information was gathered from technical journals and specification sheets from approximately 160 manufacturers. The transduction path of each sensor was determined and examined for compatibility with the transduction path diagram. The sensors examined were found to range from simple one step to complex seven step transduction paths. All were found to be compatible with the transduction path method.

A representative example of a transducer with a seven step transduction path was shown to be the Fiber Optic Spectrophone. It converts the input measurand, chemical composition, into an electrical output signal. The seven step transduction path of this device is illustrated in Figure 6.2 and is a representative example of a completed transduction path diagram.

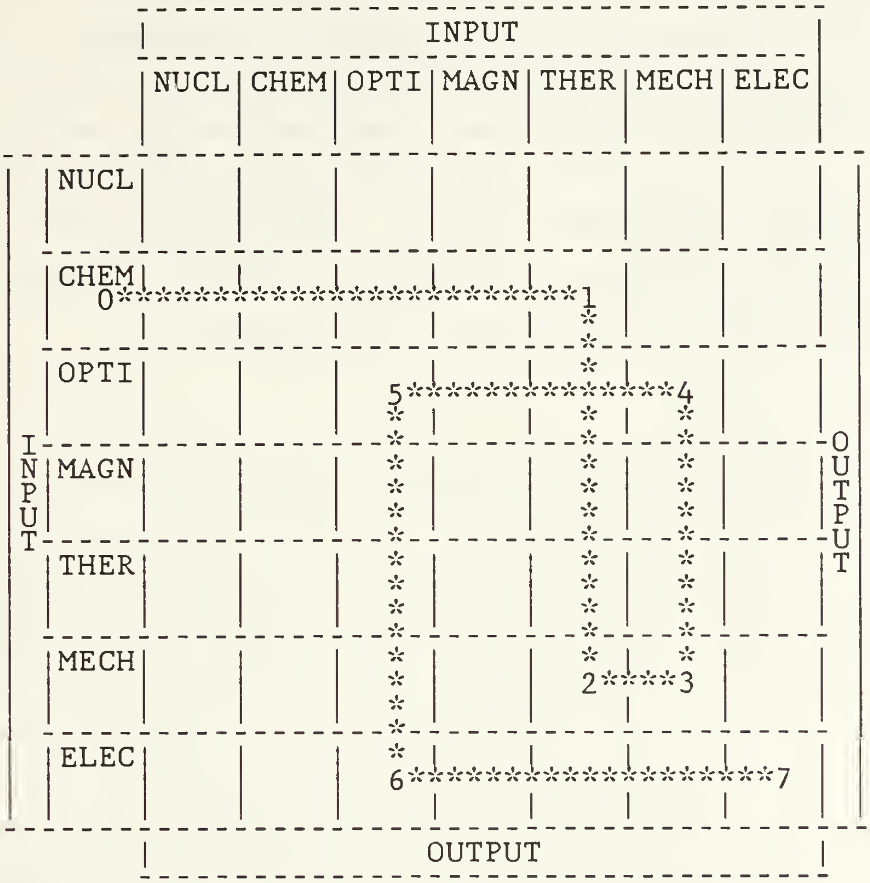
The transduction path method has been shown to be useful for sensor description and analysis. However, the method is also useful as a means of investigating sensor configurations. For any given class of sensor, the method is capable of systematically generating all possible sensor configurations utilizing the known transduction and modification principles.

		OUTPUT						
		NUCL	CHEM	OPTI	MAGN	THER	MECH	ELEC
INPUT	NUCL	1		5	1	1		6
	CHEM		2	7		4	6	11
	OPTI		2	11	1	1	1	10
	MAGN			4	2	1	4	8
	THER		2	9	1	3	1	13
	MECH	1		24	6	4	19	20
	ELEC	1	1	7	1	5	11	28

Figure 6.1 Distribution of Principles.

An investigation was carried out of all possible three step pressure sensor configurations. The techniques described in Appendix P were utilized to generate all possible transduction paths of the requisite length.

The investigation resulted in the generation of 19 possible transduction paths. One of these was discovered to be incomplete and consequently not a valid path. Ten of the paths were found to represent sensor configurations which



INPUT	0	Chemical Composition
TRANSDUCTION	0-1	PHOTOABSORPTION
	1	Temperature
TRANSDUCTION	1-2	THERMAL EXPANSION
	2	Pressure
MODIFICATION	2-3	ELASTIC DEFORMATION
	3	Strain
TRANSDUCTION	3-4	ELASTO-OPTIC EFFECT
	4	Refractive Index
MODIFICATION	4-5	PHASE INTERFEROMETER
	5	Optical Power
TRANSDUCTION	5-6	PHOTOCONDUCTIVE
	6	Resistance
MODIFICATION	6-7	SIGNAL PROCESSING
OUTPUT	7	Voltage

Fiber Optic Spectrophone

Figure 6.2 Seven Step Transducer.

currently exist and references have been cited. However, eight paths were found which do not correspond to any of the sensor types examined in the course of this project.

To the best knowledge of the author, these eight configurations have never been implemented as actual sensor designs. It is quite possible that some of the new configurations may prove to be feasible within a narrow range of applications. However, further research and appropriate paper designs would be necessary.

B. CONCLUSIONS

The transduction path method has been shown to be useful as a method of sensor analysis. Given a sensor of any type, it should be possible to generate a suitable transduction path diagram which would accurately describe the operation of that sensor. Furthermore, the method may be used to generate transduction paths and thus makes possible a systematic investigation of sensor configurations.

While the example investigation carried out in Chapter V did not reveal any new sensor configurations which were particularly promising, it did manage to generate 18 transduction paths. Ten of these paths were known sensor configurations while the other eight were not. This does, however, reinforce the idea that the transduction path method may be used to systematically survey a given class of sensors to determine if some principle is being under-utilized.

The investigation carried out is as good or as bad, of course, as the lists of principles which have been drawn up in support of the method. The listings of principles contained within this paper are as complete as the author has been able to manage. Some principles may have been overlooked and the reader may recognize gaps that need to be filled. New principles may be easily added at any time by simply making the proper entries in Chapter IV and the appendices. The study of solid state sensors is practically limitless in scope and it is hoped that this paper may prove useful as a starting point for further research in this area.

APPENDIX A

MECHANICAL PHYSICAL QUANTITIES

ACCELERATION*
acceleration, angular
acceleration, linear
ACOUSTIC ENERGY*
ACOUSTIC WAVE*
acoustic emission
acoustic power
aeroelasticity
altitude
ANGLE*
area
ATTRACTION, MAGNETIC*
brittleness
CONTRACTION, LATERAL*
DEFLECTION*
DEFORMATION*
DENSITY*
depth, liquid
detonation
DIAMETER, CONDUCTOR*
DIAMETER, WIRE*
DIMENSION*
DIPOLE ALIGNMENT*
direction
DIRECTION OF MOTION*
DISPLACEMENT*
displacement, angular
displacement, linear
distance
elasticity
ELASTIC PROPERTIES*
energy, internal
energy, kinetic
energy, potential
fatigue
FLOW*
FLOW, FLUID*
flow, gas
FLOW RATE, MASS*
flow rate, volumetric
FORCE*
fracture
FREQUENCY, ACOUSTIC*
FREQUENCY, MECHANICAL*
FREQUENCY, RESONANT*
FREQUENCY, FLEXURAL*
FREQUENCY, TORSIONAL*
FRICTION*
FRICTION, LIQUID*
FRICTION, SOLID*
HARDNESS*
hydroelasticity
IMMERSION, PARTICLE*
INCLINATION*
LENGTH*
level
LEVEL, LIQUID*
load
mass

* indicates measurand associated with principles listed in Chapter IV.

MICROBENDS*
MOMENTUM, ANGULAR*
momentum, linear
motion
MOVEMENT, AIR*
MOVEMENT, POLAR FLUID*
PATH LENGTH DIFFERENCE*
permeability
plasticity
POSITION*
POSITION, ANGULAR*
position, linear
PRESSURE*
pressure, absolute
pressure, barometric
pressure, blood
pressure, differential
pressure, gage
pressure, impact
pressure, partial
PRESSURE, SOUND*
pressure, stagnation
pressure, static
PRESTRAIN*
PROXIMITY*
PROXIMITY, CONDUCTOR*
ROTATION*
SAW*
SEPARATED GASES*
SHAPE*
SHOCK*
SOUND*
sound attenuation
sound diffraction
sound dispersion
sound energy flux
sound intensity
sound reflectivity
sound refractive index
sound scattering
specific gravity
speed
STRAIN*
STRAIN, LOCALIZED*
STRESS*
STRESS, LONGITUDINAL*
TENSION*
TENSION, SURFACE*
THICKNESS*
TORQUE*
ULTRASONIC*
vacuum
VELOCITY*
VELOCITY, ANGULAR*
VELOCITY, AIR*
VELOCITY, FLOW*
velocity, linear
VELOCITY, SAW*
velocity, sound
VIBRATION*
viscoelasticity
viscoplasticity
viscosity
VOLUME*
WAVELENGTH*
weight
work

APPENDIX B

THERMAL PHYSICAL QUANTITIES

CONDUCTIVITY, THERMAL*
diffusivity, thermal
HEAT*
heat capacity
heat flow
HEAT FLUX*
HEAT TRANSFER RATE*
infrared radiation
POINT, BOILING*
point, dew
POINT, FREEZING*
point, ice
point, sublimation
point, triple
specific heat
TEMPERATURE*
TEMPERATURE CHANGE*
TEMPERATURE, COOLING*
TEMPERATURE, DIFFERENCE*
TEMPERATURE, GRADIENT*
TEMPERATURE, NOISE*

* indicates measurand associated with principles listed in Chapter IV.

APPENDIX C

ELECTRICAL PHYSICAL QUANTITIES

admittance
CAPACITANCE*
CHARGE*
CHARGE CARRIER*
charge density
CHARGE LOSS*
CONDUCTIVITY*
CORONA DISCHARGE*
CURRENT*
current density
CURRENT, RESTORING*
CURRENT, VACUUM*
DIELECTRIC CONSTANT*
ELECTRIC FIELD*
ELECTRIC FIELD, AC*
electric flux
ELECTRONS*
EMF*
EMF, AC*
emf, analog
EMF, DC*
emf, digital
EMF, FM*
EMF, GATE*
frequency
FREQUENCY, DIFFERENCE*
FREQUENCY, ELECTRIC*
FREQUENCY, ELECTROMAGNETIC*
FREQUENCY, RESONANT*
IMPEDANCE*
INDUCTANCE*
IONIZATION*
POWER*
RADIATION, ELECTROMAGNETIC*
reactance
RESISTANCE*
RESISTANCE, GATE*
RESISTIVITY*
SPARK, ELECTRICAL*
susceptance
THERMORESISTANCE*
var
VOLTAGE*
WAVE, ELECTROMAGNETIC*
wavelength

* indicates measurand associated with principles listed in Chapter IV.

APPENDIX D

MAGNETIC PHYSICAL QUANTITIES

FLUX, CHANGE*
FLUX, DENSITY*
FREQUENCY, ELECTROMAGNETIC*
MAGNETIC FIELD*
MAGNETIC FIELD, DYNAMIC*
MAGNETIC FIELD, INTENSITY*
MAGNETIC FIELD, STATIC*
MAGNETIC INDUCTION*
MAGNETIZATION*
MAGNETIZATION DIRECTION*
MAGNETIZATION, SUDDEN*
magnetic flux
magnetic flux density
magnetomotive force
PARAMAGNETISM*
PERMEABILITY*
permittivity
RADIATION, ELECTROMAGNETIC*
reluctance
WAVE, ELECTROMAGNETIC*

* indicates measurand associated with principles listed in Chapter IV.

APPENDIX E

OPTICAL PHYSICAL QUANTITIES

ABSORPTANCE*
birefringence
COLOR, ANY*
COLOR, PRIMARY*
COUPLING COEFFICIENT*
flourescence
FREQUENCY, OPTICAL*
ILLUMINATION*
ILLUMINATION, DIFFERENCE*
IMAGE, DECEPTIVE*
IMAGE, OPTICAL*
INFRARED RADIATION*
intensity
LIGHT*
LIGHT EMISSION*
light, laser
luminance
luminous flux
luminous intensity
MAX ENERGY WAVELENGTH*
MAX POLARIZED LIGHT*
OPAQUENESS*
OPTICAL COUPLING*
OPTICAL POWER*
PHASE DIFFERENCE*
POLARIZATION*
POLARIZING ANGLE*
RADIANT HEAT*
REFLECTION COEFFICIENT*
REFLECTIVITY*
REFRACTIVE INDEX*
scattering
scintillation
SPECTRAL LINE SEPARATION*
TRANSMISSIVITY*
turbidity
ULTRAVIOLET LIGHT*
VISIBLE, LIGHT*
vision, binary
vision, color
vision, gray scale
wavelength

* indicates measurand associated with principles listed in Chapter IV.

APPENDIX F

CHEMICAL PHYSICAL QUANTITIES

acidity
alkalinity
atomic weight
BIOLOGICAL MECHANISM*
CHEMICAL COMPOSITION*
CHEMICAL REACTION*
CHEMICAL REACTION RATE*
chemical substance
CHEMICAL STATE*
CHEMICAL CONCENTRATION*
concentration, combustibles
concentration, dissolved oxygen
CONCENTRATION, GAS*
CONCENTRATION, IONIC*
CONCENTRATION, NO*
CONCENTRATION, OXYGEN*
CONCENTRATION, SALT*
CONCENTRATION, VAPOR*
CRYSTALLIZATION*
DIFFUSION RATE*
diffusivity
GAS, SAMPLE*
HUMIDITY*
humidity, absolute
humidity, relative
humidity, specific
moisture
molecular weight
OXIDATION*
solubility
SOLUBILITY, GAS*

* indicates measurand associated with principle listed in Chapter IV.

APPENDIX G

NUCLEAR PHYSICAL QUANTITIES

BOMBARDMENT, NUCLEAR
dose absorbed
FREQUENCY, ELECTROMAGNETIC*
neutron flux density
radiation, alpha
radiation, beta
radiation, cerenkov
radiation, cosmic
RADIATION, GAMMA RAY*
RADIATION, IONIZING*
RADIATION, NUCLEAR*
RADIATION, X-RAY*
radioactivity

* indicates measurand associated with principles listed in Chapter IV.

APPENDIX H

ALPHABETICAL LISTING OF PRINCIPLES

ABSORPTION (Unless otherwise indicated, see Reference 11)
chemical composition to optical power
thickness to optical power

ACOUSTIC INTERFERENCE
frequency, acoustic to acoustic energy

ACOUSTIC PROPAGATION (See Reference 26)
elastic properties to saw velocity

ACOUSTOELECTRIC (See Reference 27)
pressure, sound to emf

ADSORPTION
chemical concentration to chemical concentration

AMPERE'S LAW
current to force

AMPLITUDE MODULATION (See Reference 15)
absorptance to optical power
polarization to optical power
coupling coefficient to optical power
transmissivity to optical power
optical coupling to optical power

APD (See Reference 28)
optical power to current

ARCHIMEDE'S PRINCIPLE
density to force

ARRHENIUS EQUATION
temperature to chemical reaction rate

ATMOLYSIS
chemical composition to separated gases

BARKHAUSEN EFFECT
magnetic field to flux density

BARNETT EFFECT
rotation to magnetization

BAUSCHINGER EFFECT
prestrain to elastic properties

BECQUEREL EFFECT
illumination difference to emf

BENEDICK EFFECT
emf to temperature difference

BIOLUMINESCENCE (See Reference 29)
biological mechanism to light emission

BLACKBODY RADIATION (See Reference 30)
temperature to radiant heat

BREMSTRAHLUNG RADIATION
electrons to x-ray radiation

BREWSTER'S LAW
polarizing angle to max polarized light

BRIDGE CIRCUIT (See Reference 4)
resistance to restoring current
resistance to emf

CAPACITIVE PI-FET (See Reference 13)
charge to emf

CAPILLARY COLUMN (See Reference 31)
gas sample to separated gases

CATHODIC REDUCTION (See Reference 32)
oxygen concentration to current

CAVITATION
angular velocity to sound

CCD (See Reference 28)
optical image to emf

CERENKOV EFFECT
electrons to light emission
gamma ray radiation to light emission

CFT (See Reference 33)
gate resistance to current

CHARGE AMPLIFIER (See Reference 34)
charge to emf
charge to current

CHARGE MOBILITY (See Reference 25)
charge carrier to resistance

CHEMISORPTION (See Reference 35)
gas concentration to capacitance
NO concentration to resistance
vapor concentration to elastic properties

CHRISTIANSEN EFFECT
refractive index to optical power

COLOR MIXING
primary colors to any color

COMBUSTION (See Reference 29)
oxidation to light emission
oxidation to heat

CONDUCTIVE ELASTOMER (See Reference 19)
position to resistance
shape to resistance
force to resistance

CORBINO EFFECT
magnetic field to current

COULOMB'S LAW
proximity to optical coupling

CRAFT'S RULE
pressure to boiling point

CRYSTALLUMINESCENCE		
crystallization	to	light emission
CURIE-WEISS LAW		
temperature	to	permeability
DIFFERENTIAL TRANSFORMER (See Reference 22)		
inductance	to	emf
DIFFRACTION		
wire diameter	to	optical power
DONNAN MEMBRANE EQUILIBRIUM		
chemical concentration	to	diffusion rate
DOPPLER (ACOUSTIC)		
velocity	to	frequency, acoustic
DOPPLER (ELECTRIC)		
velocity	to	frequency, electromagnetic
DOPPLER (MAGNETIC)		
velocity	to	frequency, electromagnetic
DOPPLER (OPTICAL)		
velocity	to	frequency, optical
DOPPLER (NUCLEAR)		
velocity	to	frequency, electromagnetic
DORN EFFECT (ELECTROKINETIC)		
particle immersion	to	emf
ECKO (See Reference 36)		
impedance	to	emf
ECOLD (See Reference 36)		
impedance	to	emf
EDISON EFFECT		
temperature	to	vacuum current
EINSTEIN-DE HASS EFFECT		
sudden magnetization	to	angular momentum
ELASTIC DEFORMATION (See Reference 37)		
acceleration	to	deflection
acceleration	to	strain
acceleration	to	stress
acoustic wave	to	strain
displacement	to	position
displacement	to	strain
force	to	displacement
force	to	position
force	to	strain
pressure	to	deflection
pressure	to	displacement
pressure	to	microbends
pressure	to	position
pressure	to	proximity
pressure	to	strain
pressure	to	tension
pressure, sound	to	displacement
pressure, sound	to	position
pressure, sound	to	strain
saw	to	strain
shock	to	strain
stress	to	tension

ELASTIC DEFORMATION (continued)

strain	to	acoustic wave
strain	to	displacement
strain	to	position
strain	to	pressure, sound
strain	to	saw
strain	to	tension
stress	to	strain
tension	to	strain
torque	to	strain
vibration	to	strain

ELASTIC LIMIT

hardness	to	deformation

ELASTO-OPTIC EFFECT (See Reference 15)

strain	to	refractive index

ELECTRIC WIND EFFECT

corona discharge	to	air movement

ELECTROACOUSTIC (See Reference 27)

emf	to	pressure, sound

ELECTROCAPILLARITY

emf	to	surface tension

ELECTROCHEMICAL (See Reference 29)

chemical composition	to	charge

ELECTROLUMINESCENCE

ac electric field	to	light emission

ELECTROLYTIC DISSOCIATION

chemical concentration	to	freezing point

ELECTRO-OPTICAL EFFECT

emf	to	dielectric constant
emf	to	refractive index

ELECTRO-OSMOSIS

emf	to	polar fluid movement

ELECTROPLATING (See Reference 29)

charge	to	chemical reaction
emf	to	chemical reaction

ELECTROSTRICTIVE

emf	to	stress
emf	to	strain
electric field	to	strain

ENERGY BANDGAP SHIFT (See Reference 38)

temperature	to	absorptance

EOTVOS EFFECT

direction of motion	to	force

ETTINGSHAUSEN EFFECT

current	to	temperature difference

EVANESCENCE (See Reference 15)

position	to	coupling coefficient

FARADAY INDUCTION

flux change	to	emf
current	to	magnetic field

FARADAY ROTATION		
magnetic field	to	polarization
FERROELECTRIC		
electric field	to	dipole alignment
FISSION		
nuclear bombardment	to	radiation, electromagnetic
nuclear bombardment	to	heat
nuclear bombardment	to	optical power
nuclear bombardment	to	ionizing radiation
FLUX DENSITY (See Reference 39)		
position	to	magnetic field
FOURIER'S LAW		
temperature	to	heat flux
FTIR (See Reference 15)		
position	to	coupling coefficient
GALVANOMAGNETIC (HALL)		
static magnetic field	to	dc emf
static magnetic field	to	ac emf
dynamic magnetic field	to	ac emf
GATE CONTROLLED DIODE (See Reference 40)		
ionic concentration	to	gate emf
dielectric constant	to	gate emf
GAUSS EFFECT		
magnetic field	to	resistance
GEIGER EFFECT		
nuclear radiation	to	light emission
GLADSTONE & DALE'S LAW		
temperature	to	refractive index
stress	to	refractive index
GRAVITY PENDULUM (See Reference 41)		
inclination	to	position
HALLWOCK'S EFFECT		
ultraviolet light	to	charge loss
HENRY'S LAW		
temperature	to	gas solubility
HERTZ EFFECT		
ultraviolet light	to	electrical spark
HOT WIRE (See Reference 42)		
air velocity	to	temperature
HYDRODYNAMIC ELEMENT (See Reference 43)		
fluid flow	to	force
HYGROSCOPIC SALT (See Reference 44)		
humidity	to	resistance
IMPEDANCE		
electrical frequency	to	current
INCANDESCENCE		
heat	to	light emission
INDUCTION		
current	to	emf

INDUCTIVE EDDY CURRENT (See Reference 3)			
	proximity	to	magnetic field
INTERDIGITAL TRANSDUCER (See Reference 27)			
	saw	to	emf
	emf	to	saw
INTERFERENCE COATING			
	thickness	to	reflection coefficient
	wavelength	to	reflection coefficient
ION MOVEMENT (See Reference 45)			
	flow	to	current
ISFET (See Reference 46)			
	charge	to	current
	chemical composition	to	current
JOHNSEN-RAHBEK EFFECT			
	emf	to	friction (solid)
JONES EFFECT			
	salt concentration	to	surface tension
JOSEPHSON JUNCTION (See Reference 47)			
	infrared radiation	to	current
	magnetic field	to	current
	noise temperature	to	current
	emf	to	current
	resonant frequency	to	current
JOSHI EFFECT			
	ionizing radiation	to	current
JOULE'S LAW			
	current	to	temperature
KERR EFFECT			
	electric field	to	polarization
	electric field	to	optical power
KERR MAGNETO-OPTIC EFFECT			
	flux density	to	polarization
KOHLRAUSCH'S LAW			
	chemical concentration	to	conductivity
LAMBERT'S COSINE LAW			
	angle	to	illumination
LAMBERT'S LAW			
	thickness	to	optical power
	chemical concentration	to	optical power
LASER EXTERNAL MIRROR (See Reference 15)			
	position	to	optical power
LED ELECTRO-OPTIC (See Reference 28)			
	current	to	optical power
LENS SYSTEM (See Reference 30)			
	optical image	to	optical image
LIQUID CRYSTAL			
	temperature	to	opaqueness
	magnetic field	to	opaqueness
LORENTZ CONTRACTION			
	velocity	to	length

LUMINESCENCE			
	optical power	to	light emission
	nuclear radiation	to	light emission
	electromagnetic wave	to	light emission
MAGNETIC ANISOTROPY			
	magnetization direction	to	force
MAGNETIC SOUND DISPERSION			
	magnetic field	to	acoustic frequency
MAGNETORESISTANCE (See Reference 39)			
	magnetic field	to	impedance
MAGNETOSTRICTION			
	strain	to	magnetic field
	magnetic field	to	strain
MATTHEISSEN'S RULE			
	temperature	to	resistivity
MECHANICAL RESONANCE (See Reference 42)			
	length	to	acoustic frequency
MECHANICAL SWITCH (See Reference 20)			
	position	to	resistance
MIRAGE EFFECT			
	heat	to	deceptive image
MOS CAPACITOR (See Reference 35)			
	capacitance	to	emf
NERNST EFFECT			
	temperature gradient	to	ac emf
NTIR (See Reference 15)			
	refractive index	to	optical power
NUMERICAL APERTURE (See Reference 15)			
	displacement	to	coupling coefficient
OHM'S LAW			
	emf	to	current
	resistance	to	current
OPTICAL INTERFERENCE			
	path length difference	to	optical power
OPTICAL ROTATION			
	chemical concentration	to	polarization
	chemical composition	to	polarization
OSCILLATOR			
	resonant frequency	to	emf
	current	to	frequency, electric
	impedance	to	frequency, electric
OSMOSIS			
	chemical composition	to	pressure
PARAMAGNETISM			
	oxygen concentration	to	magnetic attraction
PELTIER EFFECT			
	current	to	temperature cooling

PHASE INTERFEROMETER (See Reference 15)

phase difference	to	optical power
refractive index	to	optical power

PHASE SHIFT OSCILLATOR (See Reference 48)

resistance	to	emf (fm)

PHOTOABSORPTION (See Reference 15)

chemical composition	to	temperature
optical power	to	temperature
radiant heat	to	temperature

PHOTOCONDUCTIVE

ionizing radiation	to	resistance
optical power	to	resistance

PHOTOELASTIC EFFECT

stress	to	polarization
strain	to	reflectivity

PHOTOEMISSIVE

ionizing radiation	to	electrons
optical power	to	charge carrier

PHOTOCHEMICAL (PHOTOGRAPHIC) (See Reference 29)

optical image	to	chemical reaction

PHOTOLUMINESCENCE

visible light	to	light emission

PHOTOMAGNETIC EFFECT

optical power	to	paramagnetism

PHOTOSYNTHESIS

light	to	chemical reaction

PHOTOVOLTAIC

ionizing radiation	to	emf
optical power	to	emf
optical power	to	electric field

PIEZOCALORIC (See Reference 26)

stress	to	heat

PIEZOELECTRIC

stress	to	emf
stress	to	charge
strain	to	emf
strain	to	charge
frequency, resonant	to	ac emf
flexural frequency	to	emf
torsional frequency	to	emf

PIEZO-OPTICAL EFFECT

stress	to	dielectric constant
stress	to	refractive index

PIEZORESISTANCE (See Reference 2)

strain	to	resistance

PIN (See Reference 28)

charge carrier	to	current

PIN PHOTOCURRENT (See Reference 49)

ionizing radiation	to	current
optical power	to	current

PINCH EFFECT		
current	to	conductor diameter
PLL (See Reference 50)		
frequency difference	to	emf
PN PIEZOJUNCTION (See Reference 25)		
strain	to	current
POISSON'S RATIO		
longitudinal stress	to	lateral contraction
POLYMER PAPA (See Reference 33)		
humidity	to	gate resistance
POTENTIOMETRIC (See Reference 21)		
dimension	to	resistance
position	to	resistance
POWER LAW (See Reference 51)		
power	to	current
current	to	power
voltage	to	power
resistance	to	power
PROXIMITY EFFECT		
conductor proximity	to	resistance
PTAT (See Reference 52)		
temperature	to	emf
PYROELECTRIC		
temperature change	to	emf
QUANTUM INTERFEROMETER (See Reference 47)		
current	to	emf
QUARTZ RESONATOR (See Reference 34)		
strain	to	resonant frequency
RADIATION DARKENING (See Reference 15)		
ionizing radiation	to	absorptance
RADIATION PRESSURE		
light	to	force
RADIATIVE LOSSES (See Reference 53)		
microbends	to	absorptance
RESISTANCE-PRESSURE EFFECT		
pressure	to	resistance
RESONANCE (See Reference 54)		
liquid level	to	flexural frequency
density	to	torsional frequency
acoustic wave	to	frequency, acoustic
RIGHI-LEDUC EFFECT		
heat transfer rate	to	temperature difference
ROTOR (See Reference 55)		
velocity, angular	to	position
SAGNAC PHASE SHIFT (See Reference 15)		
rotation	to	phase difference

SCHLIEREN GRATING (See Reference 15)
- displacement to transmissivity

SENSING COIL (See Reference 56)
- inductance to emf
- flux change to emf

SIGNAL PROCESSING
- electrical measurand to electrical measurand

SNELL'S LAW
- reflectivity to optical power

SONOLUMINESCENCE
- acoustic energy to light emission
- ultrasonic to light emission

SPARK GAP (PASCHEN'S LAW)
- emf to heat
- emf to ionization

STARK EFFECT
- electric field to spectral line separation

STEFAN-BOLTZMANN LAW
- temperature to radiant heat

TCD (See Reference 31)
- thermal conductivity to emf

THERMAL CONDUCTIVITY (See Reference 31)
- air velocity to temperature
- mass flow rate to temperature
- flow velocity to temperature
- heat transfer rate to temperature
- separated gases to temperature
- chemical composition to temperature

THERMAL EXPANSION
- temperature to volume
- temperature to pressure

THERMOCONDUCTANCE
- temperature to conductivity

THERMOELASTIC EFFECT
- stress to emf

THERMOELECTRIC (SEEBECK)
- temperature to emf
- temperature to current

THERMOMAGNETIC
- magnetic field intensity to thermoresistance

THERMO-OPTIC
- temperature to refractive index

THERMORESISTANCE (See Reference 12)
- temperature to resistance

THERMOVOLTAIC JUNCTION
- temperature to emf

TRIBOELECTRICITY
- chemical composition to emf

TRIBOLUMINESCENCE		
friction	to	light emission
pressure	to	light emission
UNIJUNCTION OSCILLATOR (See Reference 25)		
current	to	frequency, electric
VARIABLE BIREFRINGENCE (See Reference 57)		
strain	to	polarization
VARIABLE CONDUCTIVITY (See Reference 58)		
liquid level	to	resistance
VARIABLE DENSITY (See Reference 59)		
chemical concentration	to	refractive index
VARIABLE DIELECTRIC		
liquid level	to	capacitance
deflection	to	capacitance
chemical state	to	gate resistance
temperature	to	capacitance
VARIABLE OPACITY (See Reference 60)		
position	to	optical power
VARIABLE PERMEABILITY (See Reference 61)		
magnetic field	to	resonant frequency
VARIABLE REFLECTIVITY (See Reference 59)		
refractive index	to	optical power
VARIABLE REFRACTIVE INDEX (See Reference 59)		
liquid level	to	reflectivity
VARIABLE RELUCTANCE (See Reference 14)		
position	to	magnetic field
displacement	to	inductance
velocity	to	inductance
position	to	inductance
position, angular	to	inductance
VARISTOR (See Reference 62)		
emf	to	resistance
VIBRATING WIRE (See Reference 63)		
tension	to	frequency, mechanical
VILLARI EFFECT		
stress	to	magnetic induction
VORTEX SHEDDING (See Reference 64)		
air velocity	to	density
WERTHEIM EFFECT		
torque	to	emf
WIEGAND EFFECT (See Reference 14)		
magnetic field	to	flux change
WIEN EFFECT		
emf	to	conductivity
WIEN'S DISPLACEMENT LAW		
temperature	to	max energy wavelength
WINSLOW EFFECT		
emf	to	friction (liquid)

WORKMAN-REYNOLDS EFFECT
freezing point to emf

ZENER EFFECT
voltage to current

ZIRCONIUM OXIDE CELL (See Reference 65)
oxygen concentration to emf

*Unless otherwise indicated, see Reference 11 for all entries.

APPENDIX I

NUCLEAR OUTPUT PRINCIPLES

****

NUCLEAR ------------------------> NUCLEAR

FISSION

nuclear bombardment	to	radiation, electromagnetic
nuclear bombardment	to	heat
nuclear bombardment	to	optical power
nuclear bombardment	to	ionizing radiation

****

CHEMICAL -----------------------> NUCLEAR

****

OPTICAL ------------------------> NUCLEAR

****

MAGNETIC -----------------------> NUCLEAR

****

THERMAL ------------------------> NUCLEAR

****

MECHANICAL ---------------------> NUCLEAR

DOPPLER (NUCLEAR)

velocity	to	frequency, electromagnetic

****

ELECTRICAL ---------------------> NUCLEAR

BREMSTRAHLUNG RADIATION

electrons	to	x-ray radiation

****

APPENDIX J

CHEMICAL OUTPUT PRINCIPLES

****

NUCLEAR -----------------------> CHEMICAL

****

CHEMICAL ----------------------> CHEMICAL

ADSORPTION
chemical concentration to chemical concentration

DONNAN MEMBRANE EQUILIBRIUM
chemical concentration to diffusion rate

****

OPTICAL -----------------------> CHEMICAL

PHOTOCHEMICAL (PHOTOGRAPHIC)
optical image to chemical reaction

PHOTOSYNTHESIS
light to chemical reaction

****

MAGNETIC ----------------------> CHEMICAL

****

THERMAL -----------------------> CHEMICAL

ARRHENIUS EQUATION
temperature to chemical reaction rate

HENRY'S LAW
temperature to gas solubility

****

MECHANICAL --------------------> CHEMICAL

****

ELECTRICAL --------------------> CHEMICAL

ELECTROPLATING
charge to chemical reaction
emf to chemical reaction

****

APPENDIX K

OPTICAL OUTPUT PRINCIPLES

****

NUCLEAR --------------------------> OPTICAL

CERENKOV EFFECT		
electrons	to	light emission
gamma ray radiation	to	light emission
FISSION		
nuclear bombardment	to	radiation, electromagnetic
nuclear bombardment	to	heat
nuclear bombardment	to	optical power
nuclear bombardment	to	ionizing radiation
GEIGER EFFECT		
nuclear radiation	to	light emission
LUMINESCENCE		
optical power	to	light emission
nuclear radiation	to	light emission
electromagnetic wave	to	light emission
RADIATION DARKENING		
ionizing radiation	to	absorptance

****

CHEMICAL -------------------------> OPTICAL

ABSORPTION		
chemical composition	to	optical power
thickness	to	optical power
BIOLUMINESCENCE		
biological mechanism	to	light emission
COMBUSTION		
oxidation	to	light emission
oxidation	to	heat
CRYSTALLUMINESCENCE		
crystallization	to	light emission
LAMBERT'S LAW		
thickness	to	optical power
chemical concentration	to	optical power
OPTICAL ROTATION		
chemical concentration	to	polarization
chemical composition	to	polarization
VARIABLE DENSITY		
chemical concentration	to	refractive index

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* * *

OPTICAL -----------------------> OPTICAL

AMPLITUDE MODULATION			
	absorptance	to	optical power
	polarization	to	optical power
	coupling coefficient	to	optical power
	transmissivity	to	optical power
	optical coupling	to	optical power
BREWSTER'S LAW			
	polarizing angle	to	max polarized light
CHRISTIANSEN EFFECT			
	refractive index	to	optical power
COLOR MIXING			
	primary colors	to	any color
LENS SYSTEM			
	optical image	to	optical image
LUMINESCENCE			
	optical power	to	light emission
	nuclear radiation	to	light emission
	electromagnetic wave	to	light emission
NTIR			
	refractive index	to	optical power
PHASE INTERFEROMETER			
	phase difference	to	optical power
	refractive index	to	optical power
PHOTOLUMINESCENCE			
	visible light	to	light emission
SNELL'S LAW			
	reflectivity	to	optical power
VARIABLE REFLECTIVITY			
	refractive index	to	optical power

* * *

MAGNETIC -----------------------> OPTICAL

FARADAY ROTATION			
	magnetic field	to	polarization
KERR MAGNETO-OPTIC EFFECT			
	flux density	to	polarization
LIQUID CRYSTAL			
	temperature	to	opaqueness
	magnetic field	to	opaqueness
LUMINESCENCE			
	optical power	to	light emission
	nuclear radiation	to	light emission
	electromagnetic wave	to	light emission

* * *

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THERMAL -------------------------> OPTICAL

BLACKBODY RADIATION		
temperature	to	radiant heat
ENERGY BANDGAP SHIFT		
temperature	to	absorptance
GLADSTONE & DALE'S LAW		
temperature	to	refractive index
stress	to	refractive index
INCANDESCENCE		
heat	to	light emission
LIQUID CRYSTAL		
temperature	to	opaqueness
magnetic field	to	opaqueness
MIRAGE EFFECT		
heat	to	deceptive image
STEFAN-BOLTZMANN LAW		
temperature	to	radiant heat
THERMO-OPTIC		
temperature	to	refractive index
WIEN'S DISPLACEMENT LAW		
temperature	to	max energy wavelength

****

MECHANICAL --------------------> OPTICAL

ABSORPTION		
chemical composition	to	optical power
thickness	to	optical power
COULOMB'S LAW		
proximity	to	optical coupling
DIFFRACTION		
wire diameter	to	optical power
DOPPLER (OPTICAL)		
velocity	to	frequency, optical
ELASTO-OPTIC EFFECT		
strain	to	refractive index
EVANESCENCE		
position	to	coupling coefficient
FTIR		
position	to	coupling coefficient
GLADSTONE & DALE'S LAW		
temperature	to	refractive index
stress	to	refractive index
INTERFERENCE COATING		
thickness	to	reflection coefficient
wavelength	to	reflection coefficient

LAMBERT'S COSINE LAW			
	angle	to	illumination
LAMBERT'S LAW			
	thickness	to	optical power
	chemical concentration	to	optical power
LASER EXTERNAL MIRROR			
	position	to	optical power
NUMERICAL APERTURE			
	displacement	to	coupling coefficient
OPTICAL INTERFERENCE			
	path length difference	to	optical power
PHOTOELASTIC EFFECT			
	stress	to	polarization
	strain	to	reflectivity
PIEZO-OPTICAL EFFECT			
	stress	to	dielectric constant
	stress	to	refractive index
RADIATIVE LOSSES			
	microbends	to	absorptance
SAGNAC PHASE SHIFT			
	rotation	to	phase difference
SCHLIEREN GRATING			
	displacement	to	transmissivity
SONOLUMINESCENCE			
	acoustic energy	to	light emission
	ultrasonic	to	light emission
TRIBOLUMINESCENCE			
	friction	to	light emission
	pressure	to	light emission
VARIABLE BIREFRINGENCE			
	strain	to	polarization
VARIABLE OPACITY			
	position	to	optical power
VARIABLE REFRACTIVE INDEX			
	liquid level	to	reflectivity

****

****

ELECTRICAL ---------------------->		OPTICAL
CERENKOV EFFECT		
electrons	to	light emission
gamma ray radiation	to	light emission
ELECTROLUMINESCENCE		
ac electric field	to	light emission
ELECTRO-OPTICAL EFFECT		
emf	to	dielectric constant
emf	to	refractive index
KERR EFFECT		
electric field	to	polarization
electric field	to	optical power
LED ELECTRO-OPTIC		
current	to	optical power
LUMINESCENCE		
optical power	to	light emission
nuclear radiation	to	light emission
electromagnetic wave	to	light emission
STARK EFFECT		
electric field	to	spectral line separation

****

APPENDIX L

MAGNETIC OUTPUT PRINCIPLES

* * *

NUCLEAR ------------------------> MAGNETIC

FISSION

nuclear bombardment	to	radiation, electromagnetic
nuclear bombardment	to	heat
nuclear bombardment	to	optical power
nuclear bombardment	to	ionizing radiation

* * *

CHEMICAL -----------------------> MAGNETIC

* * *

OPTICAL ------------------------> MAGNETIC

PHOTOMAGNETIC EFFECT

optical power	to	paramagnetism

* * *

MAGNETIC -----------------------> MAGNETIC

BARKHAUSEN EFFECT

magnetic field	to	flux density

WIEGAND EFFECT

magnetic field	to	flux change

* * *

THERMAL ------------------------> MAGNETIC

CURIE-WEISS LAW

temperature	to	permeability

* * *

* * *

MECHANICAL ---------------------> MAGNETIC

BARNETT EFFECT		
rotation	to	magnetization
DOPPLER (MAGNETIC)		
velocity	to	frequency, electromagnetic
FLUX DENSITY		
position	to	magnetic field
INDUCTIVE EDDY CURRENT		
proximity	to	magnetic field
MAGNETOSTRICTION		
strain	to	magnetic field
magnetic field	to	strain
VILLARI EFFECT		
stress	to	magnetic induction

* * *

ELECTRICAL ---------------------> MAGNETIC

FARADAY INDUCTION		
flux change	to	emf
current	to	magnetic field

* * *

APPENDIX M

THERMAL OUTPUT PRINCIPLES

****

NUCLEAR ------------------------> THERMAL

FISSION		
nuclear bombardment	to	radiation, electromagnetic
nuclear bombardment	to	heat
nuclear bombardment	to	optical power
nuclear bombardment	to	ionizing radiation

****

CHEMICAL -----------------------> THERMAL

COMBUSTION		
oxidation	to	light emission
oxidation	to	heat
ELECTROLYTIC DISSOCIATION		
chemical concentration	to	freezing point
PHOTOABSORPTION		
chemical composition	to	temperature
optical power	to	temperature
radiant heat	to	temperature
THERMAL CONDUCTIVITY		
air velocity	to	temperature
mass flow rate	to	temperature
flow velocity	to	temperature
heat transfer rate	to	temperature
separated gases	to	temperature
chemical composition	to	temperature

****

OPTICAL ------------------------> THERMAL

PHOTOABSORPTION		
chemical composition	to	temperature
optical power	to	temperature
radiant heat	to	temperature

****

MAGNETIC -----------------------> THERMAL

THERMOMAGNETIC		
magnetic field intensity	to	thermoresistance

****

* * *

THERMAL -------------------------> THERMAL

FOURIER'S LAW		
temperature	to	heat flux
RIGHI-LEDUC EFFECT		
heat transfer rate	to	temperature difference
THERMAL CONDUCTIVITY		
air velocity	to	temperature
mass flow rate	to	temperature
flow velocity	to	temperature
heat transfer rate	to	temperature
separated gases	to	temperature
chemical composition	to	temperature

* * *

MECHANICAL ----------------------> THERMAL

CRAFT'S RULE		
pressure	to	boiling point
HOT WIRE		
air velocity	to	temperature
PIEZOCALORIC		
stress	to	heat
THERMAL CONDUCTIVITY		
air velocity	to	temperature
mass flow rate	to	temperature
flow velocity	to	temperature
heat transfer rate	to	temperature
separated gases	to	temperature
chemical composition	to	temperature

* * *

ELECTRICAL ----------------------> ELECTRICAL

BENEDICK EFFECT		
emf	to	temperature difference
ETTINGSHAUSEN EFFECT		
current	to	temperature difference
JOULE'S LAW		
current	to	temperature
PELTIER EFFECT		
current	to	temperature cooling
SPARK GAP (PASCHEN'S LAW)		
emf	to	heat
emf	to	ionization

* * *

APPENDIX N

MECHANICAL OUTPUT PRINCIPLES

* * *

NUCLEAR ------------------------> MECHANICAL

* * *

CHEMICAL -----------------------> MECHANICAL

ATMOLYSIS
chemical composition to separated gases

CAPILLARY COLUMN
gas sample to separated gases

CHEMISORPTION
gas concentration to capacitance
NO concentration to resistance
vapor concentration to elastic properties

JONES EFFECT
salt concentration to surface tension

OSMOSIS
chemical composition to pressure

PARAMAGNETISM
oxygen concentration to magnetic attraction

* * *

OPTICAL ------------------------> MECHANICAL

RADIATION PRESSURE
light to force

* * *

MAGNETIC -----------------------> MECHANICAL

EINSTEIN-DE HASS EFFECT
sudden magnetization to angular momentum

MAGNETIC ANISOTROPY
magnetization direction to force

MAGNETIC SOUND DISPERSION
magnetic field to acoustic frequency

MAGNETOSTRICTION
strain to magnetic field
magnetic field to strain

* * *

****

THERMAL -------------------------> MECHANICAL

THERMAL EXPANSION
temperature to volume
temperature to pressure

****

MECHANICAL ---------------------> MECHANICAL

ACOUSTIC INTERFERENCE
frequency, acoustic to acoustic energy

ACOUSTIC PROPAGATION
elastic properties to saw velocity

ARCHIMEDE'S PRINCIPLE
density to force

BAUSCHINGER EFFECT
prestrain to elastic properties

CAVITATION
angular velocity to sound

DOPPLER (ACOUSTIC)
velocity to frequency, acoustic

ELASTIC DEFORMATION
acceleration to deflection
acceleration to strain
acceleration to stress
acoustic wave to strain
displacement to position
displacement to strain
force to displacement
force to position
force to strain
pressure to deflection
pressure to displacement
pressure to microbends
pressure to position
pressure to proximity
pressure to strain
pressure to tension
pressure, sound to displacement
pressure, sound to position
pressure, sound to strain
saw to strain
shock to strain
stress to tension
strain to acoustic wave
strain to displacement
strain to position
strain to pressure, sound
strain to saw
strain to tension
stress to strain
tension to strain
torque to strain
vibration to strain

ELASTIC LIMIT			
	hardness	to	deformation
EOTVOS EFFECT			
	direction of motion	to	force
GRAVITY PENDULUM			
	inclination	to	position
HYDRODYNAMIC ELEMENT			
	fluid flow	to	force
LORENTZ CONTRACTION			
	velocity	to	length
MECHANICAL RESONANCE			
	length	to	acoustic frequency
POISSON'S RATIO			
	longitudinal stress	to	lateral contraction
QUARTZ RESONATOR			
	strain	to	resonant frequency
RESONANCE			
	liquid level	to	flexural frequency
	density	to	torsional frequency
	acoustic wave	to	frequency, acoustic
ROTOR			
	velocity, angular	to	position
VIBRATING WIRE			
	tension	to	frequency, mechanical
VORTEX SHEDDING			
	air velocity	to	density

* * *

ELECTRICAL ---------------------> MECHANICAL

AMPERE'S LAW	current	to	force
ELECTRIC WIND EFFECT	corona discharge	to	air movement
ELECTROACOUSTIC	emf	to	pressure, sound
ELECTROCAPILLARITY	emf	to	surface tension
ELECTRO-OSMOSIS	emf	to	polar fluid movement
ELECTROSTRICTIVE	emf	to	stress
	emf	to	strain
	electric field	to	strain
FERROELECTRIC	electric field	to	dipole alignment
INTERDIGITAL TRANSDUCER	saw	to	emf
	emf	to	saw
JOHNSEN-RAHBEK EFFECT	emf	to	friction (solid)
PINCH EFFECT	current	to	conductor diameter
WINSLOW EFFECT	emf	to	friction (liquid)

APPENDIX O

ELECTRICAL OUTPUT PRINCIPLES

****

NUCLEAR ------------------------>		ELECTRICAL
FISSION		
nuclear bombardment	to	radiation, electromagnetic
nuclear bombardment	to	heat
nuclear bombardment	to	optical power
nuclear bombardment	to	ionizing radiation
JOSHI EFFECT		
ionizing radiation	to	current
PHOTOCONDUCTIVE		
ionizing radiation	to	resistance
optical power	to	resistance
PHOTOEMISSIVE		
ionizing radiation	to	electrons
optical power	to	charge carrier
PHOTOVOLTAIC		
ionizing radiation	to	emf
optical power	to	emf
optical power	to	electric field
PIN PHOTOCURRENT		
ionizing radiation	to	current
optical power	to	current

****

****

CHEMICAL ----------------------> ELECTRICAL

CATHODIC REDUCTION			
	oxygen concentration	to	current
CHEMISORPTION			
	gas concentration	to	capacitance
	NO concentration	to	resistance
	vapor concentration	to	elastic properties
ELECTROCHEMICAL			
	chemical composition	to	charge
GATE CONTROLLED DIODE			
	ionic concentration	to	gate emf
	dielectric constant	to	gate emf
HYGROSCOPIC SALT			
	humidity	to	resistance
ISFET			
	charge	to	current
	chemical composition	to	current
KOHLRAUSCH'S LAW			
	chemical concentration	to	conductivity
POLYMER PAPA			
	humidity	to	gate resistance
TRIBOELECTRICITY			
	chemical composition	to	emf
VARIABLE DIELECTRIC			
	liquid level	to	capacitance
	deflection	to	capacitance
	chemical state	to	gate resistance
	temperature	to	capacitance
ZIRCONIUM OXIDE CELL			
	oxygen concentration	to	emf

****

```
****************************************************************

OPTICAL --------------------------> ELECTRICAL

APD
    optical power              to   current

BECQUEREL EFFECT
    illumination difference    to   emf

CCD
    optical image              to   emf

HALLWOCK'S EFFECT
    ultraviolet light          to   charge loss

HERTZ EFFECT
    ultraviolet light          to   electrical spark

JOSEPHSON JUNCTION
    infrared radiation         to   current
    magnetic field             to   current
    noise temperature          to   current
    emf                        to   current
    resonant frequency         to   current

PHOTOCONDUCTIVE
    ionizing radiation         to   resistance
    optical power              to   resistance

PHOTOEMISSIVE
    ionizing radiation         to   electrons
    optical power              to   charge carrier

PHOTOVOLTAIC
    ionizing radiation         to   emf
    optical power              to   emf
    optical power              to   electric field

PIN PHOTOCURRENT
    ionizing radiation         to   current
    optical power              to   current
****************************************************************
```

****

MAGNETIC ------------------------> ELECTRICAL

CORBINO EFFECT		
magnetic field	to	current
FARADAY INDUCTION		
flux change	to	emf
current	to	magnetic field
GALVANOMAGNETIC (HALL)		
static magnetic field	to	dc emf
static magnetic field	to	ac emf
dynamic magnetic field	to	ac emf
GAUSS EFFECT		
magnetic field	to	resistance
JOSEPHSON JUNCTION		
infrared radiation	to	current
magnetic field	to	current
noise temperature	to	current
emf	to	current
resonant frequency	to	current
MAGNETORESISTANCE		
magnetic field	to	impedance
SENSING COIL		
inductance	to	emf
flux change	to	emf
VARIABLE PERMEABILITY		
magnetic field	to	resonant frequency

****

* * *

THERMAL	------------------------>	ELECTRICAL
EDISON EFFECT		
temperature	to	vacuum current
JOSEPHSON JUNCTION		
infrared radiation	to	current
magnetic field	to	current
noise temperature	to	current
emf	to	current
resonant frequency	to	current
MATTHEISSEN'S RULE		
temperature	to	resistivity
NERNST EFFECT		
temperature gradient	to	ac emf
PTAT		
temperature	to	emf
PYROELECTRIC		
temperature change	to	emf
TCD		
thermal conductivity	to	emf
THERMOCONDUCTANCE		
temperature	to	conductivity
THERMOELECTRIC (SEEBECK)		
temperature	to	emf
temperature	to	current
THERMORESISTANCE		
temperature	to	resistance
THERMOVOLTAIC JUNCTION		
temperature	to	emf
VARIABLE DIELECTRIC		
liquid level	to	capacitance
deflection	to	capacitance
chemical state	to	gate resistance
temperature	to	capacitance
WORKMAN-REYNOLDS EFFECT		
freezing point	to	emf

* * *

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MECHANICAL --------------------->		ELECTRICAL
ACOUSTOELECTRIC		
pressure, sound	to	emf
CONDUCTIVE ELASTOMER		
position	to	resistance
shape	to	resistance
force	to	resistance
DOPPLER (ELECTRIC)		
velocity	to	frequency, electromagnetic
DORN EFFECT (ELECTROKINETIC)		
particle immersion	to	emf
INTERDIGITAL TRANSDUCER		
saw	to	emf
emf	to	saw
ION MOVEMENT		
flow	to	current
MECHANICAL SWITCH		
position	to	resistance
OSCILLATOR		
resonant frequency	to	emf
current	to	frequency, electric
impedance	to	frequency, electric
PIEZOELECTRIC		
stress	to	emf
stress	to	charge
strain	to	emf
strain	to	charge
frequency, resonant	to	ac emf
flexural frequency	to	emf
torsional frequency	to	emf
PIEZO-OPTICAL EFFECT		
stress	to	dielectric constant
stress	to	refractive index
PIEZORESISTANCE		
strain	to	resistance
PN PIEZOJUNCTION		
strain	to	current
POTENTIOMETRIC		
dimension	to	resistance
position	to	resistance
PROXIMITY EFFECT		
conductor proximity	to	resistance
RESISTANCE-PRESSURE EFFECT		
pressure	to	resistance
THERMOELASTIC EFFECT		
stress	to	emf

VARIABLE CONDUCTIVITY		
liquid level	to	resistance
VARIABLE DIELECTRIC		
liquid level	to	capacitance
deflection	to	capacitance
chemical state	to	gate resistance
temperature	to	capacitance
VARIABLE RELUCTANCE		
position	to	magnetic field
displacement	to	inductance
velocity	to	inductance
position	to	inductance
position, angular	to	inductance
WERTHEIM EFFECT		
torque	to	emf

* * *

* * *

ELECTRICAL ---------------------> ELECTRICAL

BRIDGE CIRCUIT		
resistance	to	restoring current
resistance	to	emf
CAPACITIVE PI-FET		
charge	to	emf
CFT		
gate resistance	to	current
CHARGE AMPLIFIER		
charge	to	emf
charge	to	current
CHARGE MOBILITY		
charge carrier	to	resistance
DIFFERENTIAL TRANSFORMER		
inductance	to	emf
ECKO		
impedance	to	emf
ECOLD		
impedance	to	emf
ELECTRO-OPTICAL EFFECT		
emf	to	dielectric constant
emf	to	refractive index
GATE CONTROLLED DIODE		
ionic concentration	to	gate emf
dielectric constant	to	gate emf
IMPEDANCE		
electrical frequency	to	current
INDUCTION		
current	to	emf
ISFET		
charge	to	current
chemical composition	to	current
JOSEPHSON JUNCTION		
infrared radiation	to	current
magnetic field	to	current
noise temperature	to	current
emf	to	current
resonant frequency	to	current
MOS CAPACITOR		
capacitance	to	emf

OHM'S LAW		
emf	to	current
resistance	to	current
OSCILLATOR		
resonant frequency	to	emf
current	to	frequency, electric
impedance	to	frequency, electric
PHASE SHIFT OSCILLATOR		
resistance	to	emf (fm)
PIN		
charge carrier	to	current
PLL		
frequency difference	to	emf
POWER LAW		
power	to	current
current	to	power
voltage	to	power
resistance	to	power
QUANTUM INTERFEROMETER		
current	to	emf
SENSING COIL		
inductance	to	emf
flux change	to	emf
SIGNAL PROCESSING		
electrical measurand	to	electrical measurand
SPARK GAP (PASCHEN'S LAW)		
emf	to	heat
emf	to	ionization
UNIJUNCTION OSCILLATOR		
current	to	frequency, electric
VARISTOR		
emf	to	resistance
WIEN EFFECT		
emf	to	conductivity
ZENER EFFECT		
voltage	to	current

****

APPENDIX P

TRANSDUCER INVESTIGATION METHODS

In Chapter V, the transduction path method was introduced as a means of describing the operation of existing sensors and transducers. Sensors of various path lengths were considered and a transduction path diagram was prepared for each. In this appendix, the methods will be demonstrated by which both existing and potential solid state sensor configurations may be examined.

The operation of a solid state sensor is based on a sequence of transduction and modification steps which may be described through use of the transduction path method. The transduction path starts with an input measurand and may consist of one or more transduction or modification steps. The number of steps in the transduction path is a function of the input and output measurands associated with each step. Consecutive steps are required to dovetail properly, that is, the output of the previous step must be the same as the input of the current step.

Given an input measurand, the sensor investigator needs to be able to generate all of the potential transduction paths which will give him an electrical output signal. The potential paths must be continuous and lead from the input measurand to an electrical output signal to be acceptable. Used properly, the transduction path method is capable of generating such transduction paths in a systematic manner. Furthermore, it is capable of generating transduction paths consisting of any desired number of steps, provided such paths are theoretically possible.

To aid in the procedure by which transduction paths may be generated, a transduction path tree structure is proposed. It contains the same information as a transduction path diagram, but is in a more convenient form for the path generation process. The tree illustrates all of the possible paths through the transduction path diagram which lead from a given input measurand to an electrical output signal.

The number of levels in the tree is determined by the number of steps in the desired transduction path. For each additional step in the transduction path, the number of branches in the highest level increases by a factor of seven. For example, a one step tree would have 1 branch, a two step tree would have 7 branches, and a three step tree would have 49 branches in the highest level. To further illustrate this point, one, two, and three step trees are presented below. Also presented is a tree which covers the general case of a transduction path consisting of an arbitrary number of steps.

The shortest possible transduction path consists of only one step. By definition, the one step is required to be an electrical modifier. Furthermore, the tree necessary to generate a one step transduction path consists of only a single branch as illustrated in Figure P.1. The input measurand is an electrical quantity, as is the output measurand. The number embedded in the arrow indicates the number of known principles which permit the indicated transduction or modification to occur.

To utilize the tree, one would examine the 28 electrical modification elements listed in Table XII to determine which have the proper input measurand. Once this has been accomplished, the designer would have a listing of possible one step transduction paths which lead from the desired input measurand to an electrical output signal.

A two step transduction path may consist of a transduction step followed by an electrical modifier, or it

ELEC --28--> ELEC

Figure P.1 One Step Design Tree.

may consist of a modification step followed by an electrical modifier. In either case, the last step is an electrical modifier. It is this fact which leads to the observation that the two step design tree is simply the one step tree with one additional level, or set of branches. As such, the two step tree would have 7 branches in its highest level and appear as illustrated in Figure P.2.

The input measurand may be any one of the seven forms of energy while the output measurand would be an electrical signal. The output of the first step represents an intermediate measurand which is used as the input to the second step. In this case, the intermediate measurand is electrical in nature.

To utilize the tree, one would first identify the energy form of the input measurand. Once this has been accomplished, Tables XI and XII would be examined to determine which of the transduction or modification principles listed therein have the proper input measurand. The principles so identified would be candidates for the first step of the transduction path. Their output measurands would become intermediate measurands pending the second step of the transduction path. Next, the 28 electrical modification principles in Table XII would be examined to determine which of these have input measurands compatible with the intermediate measurand noted above. These principles would be candidates for the second step of the transduction path. The candidates for the two steps would then be combined into complete transduction paths, with care taken to ensure the input and output measurands of consecutive steps mesh properly. The combinations of steps thus generated would represent a listing of all possible two step transduction paths which lead from the desired input measurand to an electrical output signal.

```
NUCL --06--> ELEC
CHEM --11--> ELEC
OPTI --10--> ELEC
MAGN --08--> ELEC   ELEC --28--> ELEC
THER --13--> ELEC
MECH --20--> ELEC
ELEC --28--> ELEC
```

Figure P.2 Two Step Design Tree.

A three step transduction path may exist in four different configurations. The first and second steps may be either transduction or modification elements. This leads to the conclusion that only four combinations are possible, since the last step has to be an electrical modifier.

In a manner similar to that of the one and two step transduction path trees described above, the three step tree is likewise an extension of the two step design tree. Another level with seven times the original number of branches is added to the two step tree. This results in a three step tree which has 49 branches in its highest level and would appear as illustrated in Figure P.3.

Once again, the input measurand may be any one of the seven forms of energy. However, in the three step tree, there are two intermediate measurands instead of only one. The outputs of the first and second steps serve as inputs to the subsequent steps and therefore are intermediate

```
NUCL --01--> NUCL
CHEM --00--> NUCL
OPTI --00--> NUCL
MAGN --00--> NUCL NUCL --06--> ELEC
THER --00--> NUCL
MECH --01--> NUCL
ELEC --01--> NUCL

NUCL --00--> CHEM
CHEM --02--> CHEM
OPTI --02--> CHEM
MAGN --00--> CHEM CHEM --11--> ELEC
THER --02--> CHEM
MECH --00--> CHEM
ELEC --01--> CHEM

NUCL --05--> OPTI
CHEM --07--> OPTI
OPTI --11--> OPTI
MAGN --04--> OPTI OPTI --10--> ELEC
THER --09--> OPTI
MECH --24--> OPTI
ELEC --07--> OPTI

NUCL --01--> MAGN
CHEM --00--> MAGN
OPTI --01--> MAGN
MAGN --02--> MAGN MAGN --08--> ELEC  ELEC --28--> ELEC
THER --01--> MAGN
MECH --06--> MAGN
ELEC --01--> MAGN

NUCL --01--> THER
CHEM --04--> THER
OPTI --01--> THER
MAGN --01--> THER THER --13--> ELEC
THER --03--> THER
MECH --04--> THER
ELEC --05--> THER

NUCL --00--> MECH
CHEM --06--> MECH
OPTI --01--> MECH
MAGN --04--> MECH MECH --20--> ELEC
THER --01--> MECH
MECH --19--> MECH
ELEC --11--> MECH

NUCL --06--> ELEC
CHEM --11--> ELEC
OPTI --10--> ELEC
MAGN --08--> ELEC ELEC --28--> ELEC
THER --13--> ELEC
MECH --20--> ELEC
ELEC --28--> ELEC
```

Figure P.3   Three Step Design Tree.

measurands. The first intermediate measurand may be any one of the seven forms of energy. However, the second intermediate measurand must be electrical in nature. This is due to the fact that the last step is required to be an electrical modifier.

To utilize the tree, one would first identify the energy form of the input measurand. Once this has been accomplished, Tables IX through XVII would be examined to determine which of the transduction or modification principles listed therein have the proper input measurand. The principles so identified would be candidates for the first step of the transduction path. Their output measurands would become intermediate measurands, pending the second step of the transduction path.

At this point, Tables XI and XII would be examined to determine which of the transduction or modification principles listed therein have an input measurand which corresponds to the first intermediate measurand identified above. The principles so identified would be candidates for the second step of the transduction path. Their output measurands would become intermediate measurands, pending the third step of the transduction path.

Finally, the 28 electrical modification principles in Table XII would be examined to determine which of these have input measurands compatible with the second intermediate measurand noted above. These principles would be candidates for the third step of the transduction path.

The candidates for the three steps would then be combined into complete transduction paths, with care taken to ensure the input and output measurands of consecutive steps mesh properly. The sequences of steps resulting from this combination process would represent all possible three step transduction paths which lead from the desired input measurand to an electrical output signal.

In Chapter V, examples of existing transducers were presented which had transduction paths up to seven steps in length. However, thus far in this appendix, design trees capable of handling transduction paths of only three steps or less have been presented. What is necessary is a general case design tree capable of handling any length of transduction path.

The key to the development of such a tree is recognition of the fact that the branches of the tree repeat in all but the lowest two levels. Examination of the three step design tree illustrated in Figure P.3 reveals that the third, or highest level, consists of entries from Tables IX through XVII. Table XVII, with all nuclear output measurands, appears at the top left of the three step tree while Tables XI and XII, with all electrical output measurands, appear at the bottom left.

Extrapolating to the case of a four step tree, it becomes apparent that the fourth level would simply be the third level repeated seven times. An entire block of tables with Table XVII at the top and Tables XI and XII at the bottom is appended to the left of each table in each level until the desired number of levels is achieved. The completed structure would appear as illustrated in Figure P.4.

As stated earlier, the second level will always consist of principles which have an electrical output measurand. It is for this reason that the second level may be represented by Tables XI and XII. Likewise, the first level, or last step in a transduction path, will always be an electrical modifier. It is for this reason that the last step is represented by the words "Signal Processing".

To utilize the general case design tree, the same procedure is followed as was utilized in the three step design tree. The only factor that will vary is the number

```
--TABLE XVII-----
--TABLE XVI-----|
--TABLES XIV,XV-|
--TABLE XIII----|-TABLE XVII-----
--TABLE X-------|               |
--TABLE IX------|               |
--TABLES XI,XII--               |
                                |
--TABLE XVII-----               |
--TABLE XVI-----|               |
--TABLES XIV,XV-|               |
--TABLE XIII----|-TABLE XVI-----|
--TABLE X-------|               |
--TABLE IX------|               |
--TABLES XI,XII--               |
                                |
--TABLE XVII-----               |
--TABLE XVI-----|               |
--TABLES XIV,XV-|               |
--TABLE XIII----|-TABLES XIV,XV-|
--TABLE X-------|               |
--TABLE IX------|               |
--TABLES XI,XII--               |
                                |                    P
--TABLE XVII-----               |                    R
--TABLE XVI-----|               |                  S O
--TABLES XIV,XV-|               |                  I C
--TABLE XIII----|-TABLE XIII----|-TABLES XI,XII--> G E
--TABLE X-------|               |                  N S
--TABLE IX------|               |                  A S
--TABLES XI,XII--               |                  L I
                                |                    N
--TABLE XVII-----               |                    G
--TABLE XVI-----|               |
--TABLES XIV,XV-|               |
--TABLE XIII----|-TABLE X-------|
--TABLE X-------|               |
--TABLE IX------|               |
--TABLES XI,XII--               |
                                |
--TABLE XVII-----               |
--TABLE XVI-----|               |
--TABLES XIV,XV-|               |
--TABLE XIII----|-TABLE IX------|
--TABLE X-------|               |
--TABLE IX------|               |
--TABLES XI,XII--               |
                                |
--TABLE XVII-----               |
--TABLE XVI-----|               |
--TABLES XIV,XV-|               |
--TABLE XIII----|-TABLES XI,XII--
--TABLE X-------|
--TABLE IX------|
--TABLES XI,XII--
```

Figure P.4 General Case Design Tree.

of intermediate measurands. For example, a four step transduction path would have three intermediate measurands, while a ten step transduction path would have nine intermediate measurands.

APPENDIX Q

SECONDARY MEASURANDS

In order to fully evaluate the relative advantages and disadvantages of various proposed transduction paths, it is necessary to consider secondary measurands. Secondary measurands may be defined as those physical quantities which are transduced or modified simultaneously with the desired input measurand. For example, the piezoelectric effect is often utilized in transducers to measure a mechanical strain. Unfortunately, the piezoelectric effect is also susceptible to thermal and electrical influences which will affect the manner in which strain is measured.

Thus far, the main transduction path has been illustrated by a series of asterisks (****) on the transduction path diagram which connect consecutive numbers. However, in order to show the effect of secondary measurands on the transduction path diagram, a new convention needs to be set. Henceforth, paths followed by secondary measurands through the transduction path diagram will be indicated by a series of dots (....). In order to illustrate the necessary techniques, an example of a sensor which is susceptible to secondary measurands is presented below.

An example of a sensor which may be influenced by secondary measurands is the piezoelectric pressure sensor. The transduction path consists of a modification followed by a transduction and a modification. The first step is elastic deformation, which converts pressure to a mechanical strain. The second step is the piezoelectric effect which converts a mechanical strain to an electrical charge. The last step is an electrical modifier which is chosen to convert electrical charge to a suitable electrical output signal.

The principle of elastic deformation is susceptible to temperature as a secondary measurand. As the temperature of an elastic device is raised or lowered, the elastic properties change. This decalibrates the device and causes a larger or smaller strain to be generated than would otherwise be expected. Therefore, temperature is an undesirable, or secondary, measurand which changes the desired output measurand. This may be illustrated on the transduction path diagram by a series of dots which lie parallel to the main transduction step. In this case, the new line would begin in the thermal input measurand block on the left side of the diagram and terminate in the mechanical output column as seen in Figure Q.1.

The piezoelectric effect is susceptible to both thermal and electrical influences as secondary measurands. As the temperature of a piezoelectric film is raised or lowered, the electrical properties change. Since the piezoelectric effect is reversible, the application of an electric field will tend to increase or decrease the strain actually developed as a result of pressure. Furthermore, how well a piezoelectric film is isolated from its surroundings will affect the manner in which charge is lost through bleed-off paths. This will degrade the DC response of a piezoelectric film and cause decalibration over a period of time as charge is lost. These undesirable effects are illustrated in Figure Q.1.

In summary, the mechanical strain generated by the first step of the transduction path is affected by changes in operating temperature. The amount of charge generated by the second step is affected by changes in temperature, electric fields, and the presence of electrical bleed-off paths. With adequate knowledge of the principles involved it should be possible to determine if compensation for secondary effects is required.

```
       ------------------------------------
       |              INPUT               |
       ------------------------------------
       |NUCL|CHEM|OPTI|MAGN|THER|MECH|ELEC|
       |    |    |    |    |  1 |    | 11 |
       |    |    |    |    |  . |    | .. |
------------------------------.--------..----
| |NUCL|    |    |    |    |  . |    | .. | |
| |    |    |    |    |    |  . |    | .. | |
| |    |    |    |    |    |  . |    | .. | |
| ----------------------------.--------..-- |
| |CHEM|    |    |    |    |  . |    | .. | |
| |    |    |    |    |    |  . |    | .. | |
| |    |    |    |    |    |  . |    | .. | |
| ----------------------------.--------..-- |
| |OPTI|    |    |    |    |  . |    | .. | |
| |    |    |    |    |    |  . |    | .. | |
| |    |    |    |    |    |  . |    | .. | |
|I----------------------------.--------..--O|
|N|MAGN|    |    |    |    |  . |    | .. |U|
|P|    |    |    |    |    |  . |    | .. |T|
|U|    |    |    |    |    |  . |    | .. |P|
|T----------------------------.--------..--U|
| |THER|    |    |    |    |  . |    | .. |T|
| |  0.............................1 | .. | |
| |    |    |    |    |    |  . |    | .. | |
| ----------------------------.--------..-- |
| |MECH|    |    |    |    |  . |    | .. | |
| |  0*****************************1 | 2. | |
| |    |    |    |    |    |  . |  * |  . | |
| ----------------------------.----*----.-- |
| |ELEC|    |    |    |    |  . |  * |  . | |
| |    |    |    |    |    |  2 |  2 |  2 | |
| |    |    |    |    |    |    |    |    | |
---------------------------------------------
       |              OUTPUT              |
       ------------------------------------

INPUT           0      Pressure
MODIFICATION    0-1    ELASTIC DEFORMATION
                1      Strain
TRANSDUCTION    1-2    PIEZOELECTRIC
OUTPUT          2      Charge
```

Figure Q.1 Secondary Measurand Diagram.

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